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DTU Environment
Department of Environmental Engineering

PhD Thesis
February 2011

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Dedicated to my son Marco,
born during this PhD study

"*If we have to wait for clear-cut and indisputable results from science, we may have to wait forever. If decisions are going to be made, they need to be made on a less than perfect basis. LCA and other tools for environmental systems analysis can contribute to the basis for such decisions, not by making it complete but by making it more comprehensive.*" Ekvall, *et al.,* 2007[1].

Preface

The work reported in this PhD thesis, entitled "Life-cycle modelling of waste management in Europe: tools, climate change and waste prevention", was undertaken at the Department of Environmental Engineering at the Technical University of Denmark, with Professor Thomas Højlund Christensen as supervisor and Professor Michael Hauschild as co-supervisor. The part-time PhD research took place from October 2006 to November 2010 and was funded by the 3R (Residual Resources Research) research school at the Technical University of Denmark.

The content of the PhD thesis is based on three papers published in academic literature and one submitted. In the text, the papers are referred to by the names of the authors and their appendix number, written with Roman numerals.

I **Gentil**, E. C., Damgaard, A., Hauschild, M. Finnveden, G. Eriksson, O., Thorneloe, S., Kaplan, P. O., Barlaz, M., Muller, O., Matsui, Y. Ii, R. and Christensen, T. H. (2010) Models for waste Life Cycle Assessment: review of technical assumptions. Waste Management, 30, 2636-2648.

II **Gentil**, E. C., Aoustin, E. and Christensen, T. H. (2009) Greenhouse gas accounting and waste management. Waste Management & Research, 27, 696-706.

III **Gentil**, E. C., Clavreul, J. and Christensen, T. H. (2009) Global warming factor performance of MSW management in Europe. Waste Management & Research, 27, 850-860.

IV **Gentil**, E. C., Gallo, D. and Christensen, T. H. (2010) Environmental evaluation of municipal waste prevention. Submitted to Environmental Science and Technology.

In addition, the following publications were produced during the PhD study:

Christensen, T. H., **Gentil**, E. C., Boldrin, A., Larsen, A. W., Weidema, B. P., Hauschild, M. (2009) C balance, carbon dioxide emissions and global warming potentials in LCA-modeling of waste management systems. Waste Management & Research, 27, 707-715.

Scheutz, C. H., Kjeldsen, P. and **Gentil**, E. C. (2009) Greenhouse gases, radiative forcing, global warming potential and waste management – an introduction. Waste Management & Research, 27, 716-723.

Gentil, E. C., Potter, A. and Boldrin, A. (2008) Carbon footprinting of export of second-life materials using life-cycle thinking. Proceeding Waste 2008. Waste and resource management: A shared responsibility. Stratford upon Avon, UK.

February 2011
Emmanuel C. Gentil

The papers are not included in this web version but can be obtained from the library at DTU Environment. Contact information: Library, Department of Environmental Engineering, Technical University of Denmark, Miljoevej, Building 113, DK-2800 Kgs. Lyngby, Denmark or library@env.dtu.dk.

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I wish to thank my supervisor Professor Thomas Højlund Christensen for the numerous constructive discussions that we shared over the years to develop this thesis. I am also grateful for his support to keep me focused on the key elements of my research. I am finally thankful to him for enabling me to contribute to a number of international workshops on climate change and waste management.

I am also indebted to Professor Michael Hauschild, my co-supervisor, who has discussed with me a number of methodological issues on LCA, especially concerning integration of waste prevention in life cycle thinking.

My PhD research would not have had been as fun and as intellectually stimulating without the various informal and formal discussions organised within the Solid Waste Research Group and the 3R Graduate School, at DTU Environment. Thanks in particular to Alessio Boldrin for exchanging thoughts on the carbon cycle, Anders Damgaard for waste LCA methodology, Simone Manfredi for landfill LCA, and Thilde Frueragaard for waste LCA and energy issues.

Many thanks for the kind support of Marianne Bigum who has diligently translated the summary of this thesis.

I would also like to take the opportunity to thank the master students who worked with me over the years during my PhD and in particular, Daniele Gallo, Julie Clavreul, Xavier le Mestre, Karin Hartling and Laurence Hamon.

Many thanks also go to Lisbet Brusendorff and Torben Dolin from the graphic office, who produced all illustrations in the papers and the thesis.

Finally and most importantly, I am thankful for the immense support, encouragement and patience that my wife Ellen has given me at all time.

List of Acronyms

AAU	Assigned allowance unites
AGW	Anthropogenic global warming
AR	Assessment report
CCX	Chicago Climate Exchange
CDM	Clean development mechanism
CER	Certified emissions reductions
CLRTAP	Convention on long-range transboundary air pollution
COM	Communication
COP	Conference of the parties
CORINAIR	Core inventory of air emissions
CSR	Corporate social responsibility
DE	Germany
DEFRA	Department for Environment, Food and Rural Affairs
DG	Directorate General
DK	Denmark
DST	Decision support tool
DTU	Technical University of Denmark
EASEWASTE	Environmental assessment of solid waste systems and technologies
EC	European Commission
EEA	European Environmental Agency
EEC	European Economic Community
ELCD	European life cycle database
ENEA	Italian National agency for new technologies, Energy and sustainable economic development
EpE	Entreprises pour l'Environnement
EPER	European pollutant emission register
EPIC-CSR	Environment and Plastics Industry Council, Corporations Supporting Recycling
ERU	Emission reduction units
ESRL	Earth System Research Laboratory
ETS	Emissions trading scheme
EU	European Union
FR	France
GDP	Gross domestic product
GEMIS	Global emission model of integrated systems
GHG	Greenhouse gas
GJ	GigaJoule
GR	Greece
GRI	Global reporting initiative
GTP	Global temperature change potential
GWF	Global warming factor
GWP	Global warming potential
ICLEI	International Council for Local Environmental Initiatives
IGES	Institute for Global Environmental Strategies
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

ISWA	International Solid Waste Association
IWM	Integrated waste management
JI	Joint implementation
JVETS	Japan's voluntary emissions trading scheme
LCA	life-cycle assessment
LCC	Life-cycle costing
LCI	Life-cycle inventory
LHV	Lower heating value
MBT	Mechanical biological treatment
MS	Member states
MSW	Municipal solid waste
MSWI	Municipal solid waste incinerator
NIMBY	Not in my back yard
NOAA	National Oceanic and Atmospheric Administration
OECD	Organisation for Economic Co-operation and Development
ORWARE	Organic waste research
PL	Poland
POP	Persistent organic pollutant
PRTR	Pollutant release and transfer registers
SSWMSS	Strategic waste management support software
TJ	Terajoule
TS	Total solid
UK	United Kingdom
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UOD	Upstream operating downstream
USA	United States of America
VS	Volatile solid
WBCSD	World Business Council on Sustainable Development
WEEE	Waste electrical and electronic equipment
WISARD	Waste integrated systems assessment for recovery and disposal
WRAP	Waste and Resources Action Programme
WRATE	Waste and resources assessment tool for the environment
WRI	World Resources Institute

Summary

Europe has a long history of waste management, where regulation, implementation and enforcement have been the main drivers for the development and diversification of waste management technologies since the late 70s. Despite strong engineering development to minimise impacts to human health and the environment, waste generation and waste 'complexity' has increased with economic development. In recent years, the European waste industry has experienced profound and lasting transformation: the growth rate of waste generation has weakened and, most importantly, a significant shift has taken place from waste disposal to resources management, requiring modelling tools, such as life-cycle assessment (LCA) models, for carrying out environmental assessment, because of the complexity of the systems.

A review of the key waste LCA models was performed in the present PhD project and showed that the results of these models most importantly depend on the technical assumptions and parameters defining waste management technologies. Some of these technical assumptions have evolved significantly from the early models to the more recent ones.

An important purpose of waste LCA models is to perform environmental assessments of waste management systems and communicate the outcomes to develop evidence-based waste management policy. Global warming potential is an environmental indicator routinely modelled in LCA tools, but also reported by a number of other accounting protocols, leading to potential confusion. In this thesis, a review of the different waste management and greenhouse gases accounting mechanisms was carried out and a reporting framework, called the upstream-operating-downstream, or 'UOD' framework, proposed.

As a mean of illustration, the global warming factor of six European member states was modelled. The outcome of the study indicates that, despite a common 'minimum' regulatory regime, the performance of waste management systems is very different among member states. The best performing member states are the nations which have promoted efficient material and energy recovery, leading to significant benefits to society, due to the substitution of primary resources. Another finding is that it is more robust to evaluate the waste management performance of member states by using environmental indicators (loads and benefits), rather than simply using the proportion of waste management technologies operated by each member state (structural indicators).

Managing waste appropriately generates environmental benefits, leading to the comforting, and potentially misleading impression that waste generation is acceptable, as long as environmental value is gained from the recovery of materials and energy. However, it is quite clear that, if waste is not produced in the first place, through waste prevention activities, waste management impacts and benefits cease to exist. Problem solved. The issue is that a ‘waste free’ or a ‘zero waste’ society is a purely abstract concept that has little value at the policy level. Partial waste prevention is, nevertheless, a more realistic approach, currently embraced by European policy makers and defined as the highest priority of the waste hierarchy, according to the framework directive on waste. Waste prevention is, however, poorly implemented and little environmental quantification has been performed. To address this issue, a conceptual waste prevention model is provided in this thesis and applied to the waste LCA model, EASEWASTE. The main outcome of the research indicates that relatively small levels of waste prevention reduce environmental loads and benefits of waste management systems (not necessarily proportionally). Furthermore, significant environmental savings are observed from the avoided production of goods (upstream from waste management) due to waste prevention. More specifically, the study showed that the prevention of meat waste generates the highest environmental savings, compared to vegetable waste, beverage packaging and unsolicited mail.

Keywords: municipal solid waste, MSW, waste management system, life-cycle assessment, LCA, greenhouse gas, GHG, global warming potential, GWP, global warming factor, GWF, waste prevention.

Dansk sammenfatning

Europa har en lang tradition for affaldshåndtering, hvor regulering, implementering og håndhævelse har været de primære værktøjer siden slutningen af 70'erne. Til trods for stor ingeniørmæssig indsats for at minimere sundhedsmæssige og miljømæssige påvirkninger, øges affaldsgenereringen og "affaldskompleksiteten" fortsat i takt med den økonomiske udvikling. I de seneste år har den europæiske affaldsindustri dog oplevet en markant og vedvarende forandring: Affaldsgenereringen stiger ikke i så høj en grad som tidligere, og mere vigtigt, et signifikant skift er sket, således at affald nu ikke længere ses som noget, der blot skal bortskaffes men anses som en ressource, der skal håndteres. Dette medfører et behov for udvikling af modelleringsværktøjer, såsom livscyklusvurdering (LCV), til at lave miljømæssige vurderinger af affaldshåndteringen.

En evaluering af de mest benyttede LCV-værktøjer, udført i dette ph.d.-projekt viste, at de miljømæssige påvirkninger primært afhænger af de tekniske antagelser og parametre brugt til at definere affaldshåndteringsteknologierne. En del af disse antagelser og parametre har udviklet sig væsentligt fra de tidlige modeller til de nyest udviklede modeller. Et vigtigt formål med værktøjer til LCV er at foretage en miljømæssig vurdering af affaldshåndteringssystemerne og at viderekommunikere resultaterne, så de kan bruges til at udvikle videnbaseret politik for affaldshåndtering.

Potentiel global opvarmning er en miljøindikator, som rutinemæssigt bruges i LCV værktøjer, men som også rapporteres i flere andre metoder, hvilket kan føre til forvirring på grund af forskelligeheder i de bagvedliggende metoder . I dette projekt vurderes forskellige affaldshåndterings- og drivhusgas-redegørelsesmetoder og en rapporteringsstruktur benævnt opstrøm-proces-nedstrøm 'OPN' foreslås. Den globale opvarmningsfaktor for seks EU medlemslande er modelleret i dette projekt. Resultaterne indikerer, at der på trods af et fælles overordnet europæisk regulatorisk regime, er store forskelle på miljøpåvirkningen for affaldshåndteringssystemer medlemslandene imellem. De medlemslande, som præsterer bedst med hensyn til potentiel global opvarmning, er de nationer, som har indført effektiv ressource og energigenvinding, førende til signifikante fordele for samfundet, da ikke-fornybare råstoffer derved substitueres. Et andet resultat er, at det er mere robust og korrekt at evaluere den

miljømæssige præstation af affaldshåndteringen i medlemslandene ved at bruge miljømæssige indikatorer (byrde og fordel), i stedet for blot en generel rangering baseret på hvor store mængder affald de forskellige affaldshåndteringsteknologier håndterer i hvert af medlemslandene (strukturelle indikatorer i forhold til affaldshierarkiet).

En korrekt håndtering af affald medfører miljømæssige fordele, så længe miljømæssig værdi opnås ved at genvinde ressourcer og energi. Dette kunnelede til det misvisende indtryk, at affaldsproduktion er acceptabel.. Det står dog rimelig klart, at hvis affaldet aldrig var blevet produceret på grund af affaldsforebyggende tiltag, så ville de miljømæssige byrder og fordele ophøre med at eksistere. Konceptet "affaldsløst" eller "zero waste" samfund er dog meget abstrakt, og er ikke realistisk. Delvis affaldsforebyggelse er derimod en mere realistisk tilgang, som på nuværende tidspunkt har fundet accept hos de politiske beslutningstagere i Europa, og er derfor defineret som havende den højeste prioritet i affaldshierarkiet ifølge de rammer, der er sat i affaldsdirektivet. Affaldsforebyggelse er til dato ikke godt implementeret og meget lille miljømæssig kvantificering er blevet gjort. For at adressere dette er en konceptuel affaldsforebyggelsesmodel foreslået og anvendt i affalds LCV værktøjet EASEWASTE. Det primære resultat af denne forskning indikerer at relativt små niveauer af affaldsforebyggelse reducerer affaldshåndteringssystemernes miljømæssige byrder og fordele (ikke nødvendigvis proportionalt). Desforuden blev signifikante miljømæssige besparelser fundet ved at undgå produktionen af varer (opstrøms i forhold til affaldshåndteringen) pga. affaldsforebyggelse. Studiet viste helt præcist at forebyggelsen af kødaffald medførte de største miljømæssige besparelser sammenlignet med forebyggelse af grøntsagsaffald, drikkevarebeholdere og husstandsomdelte reklamer.

Nøgleord: Husholdningsaffald, affaldshåndteringssystemer, livscyklusvurdering (LCV), drivhusgasser, potentiel global opvarmning, affaldsforebyggelse.

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Introduction

Waste is generally considered as an inconvenient and unwanted by-product of society. From an engineering point of view, waste is a conscious or unconscious failure in optimisation somewhere in the supply chain. For industry, waste is rarely fully internalised, from an economist point of view. In most countries, if not all, gross domestic product (GDP) growth (reflected in population growth, urbanisation and affluence levels) is correlated to increased waste production. GDP is actually used a proxy to evaluate waste production[2]. The management of waste is generally considered as a necessary mean to protect human health, and the environment. Strict regulatory regime, followed by strict implementation and enforcement has led to higher standards of waste management. A good example is the development of integrated waste management policy in the European Union (EU), although not enforced uniformly across all the member states. For instance, in the last 20 years, Europe has experienced a drastic improvement in the management of its waste: more diversified technologies and a recent slowing down of the municipal waste growth, albeit still increasing[3]. In the Organisation for Economic Co-operation and Development (OECD) countries, municipal waste growth has been higher[4]. In industrialised nations, and more specifically in Europe, the management of waste has gone from a simple control of pollution to preserve human health and the environment, to a more sophisticated optimisation of materials and energy recovery (sometimes called “valorisation" from the French) that substitutes products manufacture and energy production elsewhere in society, while minimising detrimental environmental impacts. This change can be inferred from the increase of incineration (with electricity and heat recovery) capacity[5], improved recycling rates[6], increased composting[7] and optimised gas recovery (for electricity production) from landfills[8]. For instance, energy production from biodegradable municipal waste has almost quadrupled between 1990 and 2008, from 171,776 TJ to 621,656 TJ (net calorific value)[9]. In contrast, increased emissions have occurred in the same period in low, middle-range income and fast developing countries[10, 11].

Waste management, has evolved drastically in the last three decades due to diversification of waste management technologies in a few regions of the world with a strongly regulated emission control and intensification of waste dumping in emerging countries with poor regulation and poor environmental control. Coincidently, in the same period, but not directly linked, anthropogenic global warming has become an increasing problem for society. In 1975, Broecker was one of the first scientists to define anthropogenic global warming and its influence on the global climate change[12].

Atmospheric CO_2 concentration have increased from 316 ppm in 1960 to 387 ppm in 2009, equivalent to an increase of 22% for the Mona Loa record (longest record of atmospheric CO_2 monitoring)[13]. Globally, atmospheric CO_2 ranged from 339 ppm in 1980 to 386 ppm in 2009, or an increase of 14%[14]. Anthropogenic global methane emissions (a strong short-lived greenhouse gas), arguably more relevant to the waste industry from landfill emissions, is the second most important greenhouse gas (GHG) after CO_2 emissions. It is estimated that global landfill methane emissions have increased from 550 $MtCO_2$-eq in 1990 to 700 $MtCO_2$-eq in 2010, or an increase of 27 %[15] over that period.

The direct contribution of post-consumer waste (mainly from fugitive methane emissions of landfills) remains relatively small but not insignificant on a global scale, accounting for less than 5% of the total GHG emissions, or 1300 $MtCO_2$-eq in 2005[15]. Waste management activities have been regulated relatively early in the development of environmental regulations, because of their associated impacts on human health and the degradation of the environment. These regulations are probably the strictest and most comprehensive among environmental legislation in Europe, with the exception of the nuclear industry. This strong regulation of the waste industry has, without doubt, been a significant driver behind the radical change that the industry has experienced and has evolved from a simple but constraining control of emissions towards a greater understanding of the potential benefits of energy and material recovery. It is believed that the environmental optimisation of energy and material recovery from waste activities can only be made possible by the environmental assessment of waste management from a system perspective[16]. One of the approaches to achieve this is to use life cycle assessment (LCA) applied to waste management[16,17]. The development of LCA has enabled us to develop evidence concerning the potential environmental benefits of appropriate waste management by considering waste as a useful resource to initiate circular economy where waste produced somewhere becomes a resource elsewhere in society, while respecting the environment.

Rationale and research objectives

The overall objective of the research is to investigate the environmental performance of waste management in Europe, by means of life-cycle thinking methodology. More specifically, the research focuses on three themes:

- understanding the underlying assumptions behind waste LCA models (Chapter 2);
- evaluating the implications of waste management on climate change (Chapter 3); and
- assessing the environmental performance of municipal waste prevention (Chapter 4).

The rationale behind these objectives is based on the evolution of waste and waste management in Europe (Chapter 1), necessitating robust models (Chapter 2) for assessing the environmental performance of waste management activities. This is the necessary pre-requirement for interpreting differences in results with other models and providing good evidence for determining environmental loads and benefits of waste activities, such as, but not limited to, global warming potential. This leads to the second objective (Chapter 3). While anthropogenic global warming (AGW) is not a new phenomenon and is not the only environmental impact, it has recently gained considerable importance at political and policy levels, due to the increased global urgency of this impact. Modern engineered waste management certainly plays a bigger role (think benefits from waste management) than previously reported. In addition to pollution abatement (incinerator air pollution control, landfill liner, ...) and environmental benefits (recovered materials and energy) of integrated waste management systems, it is imperative to assess the environmental consequences of actually preventing the waste from being produced in the first place, as the environmental quantification of prevention is poorly understood. This is the rationale behind the third research objective (Chapter 4).

The research encompasses conceptual approach, modelling and implementation of theoretical framework that could support further evidence for waste management policy making within Europe. The purpose of the research is to demonstrate and communicate that waste, if managed intelligently and appropriately, can be used as a valuable resource, substituting raw materials and fossil energy sources, substantially reducing local and global environmental impacts.

Structure of the thesis

Chapter 1 provides a contextual overview of municipal waste in Europe, including quantity and treatment, as well as a short summary of the European legislative framework. This provides the necessary background to understand the drivers and the basis of the research.

Chapter 2 presents the findings of the waste LCA model comparison with an analysis on the different types of assumptions and their specificity. The advantage of the system LCA models, as opposed to other more simple LCA models for assessing integrated waste management system, is emphasised. Methodological aspects of waste LCA modelling are also discussed.

Chapter 3 highlights the relationship between waste management and climate change. This includes a proposed reporting framework of GHG emissions for various waste stakeholders, an environmental assessment of GHG emissions and savings from the waste industry in selected European member states and a discussion on specific methodological issues.

Chapter 4 includes an environmental assessment of municipal waste prevention, where a conceptual model is proposed. The environmental benefits of waste prevention, as well as the small environmental loads are demonstrated, providing further evidence of the importance of waste prevention in waste policy.

The research results presented in the PhD thesis are a synopsis of four scientific papers enclosed in the appendix.

1 Waste in Europe: An ever changing landscape

Waste and waste management have changed quite radically in Europe since 1975 (Inception date of the first Waste Framework Directive, 75/442/EEC). This profound evolution in the European waste landscape is the main driver for the research work undertaken in this thesis. The general environmental pressures from human activities have evolved significantly (mainly due to the increasing economic throughput and increasing population. The waste management landscape like any human activities has evolved drastically too.

1.1 Increased environmental pressures

It is quite clear that there have been a significant increase in environmental pressures on a global level. It has recently been shown that three global environmental pressures have exceeded safe humanity threshold, namely biodiversity loss, climate change, and nutrient cycle perturbation[18]. In Europe, a reduction of some pressures has been experienced: reduction of lead, chlorofluorocarbons and NOx emissions, increase treatment of urban wastewater, increased conservation areas and forestry. Simultaneously, an increase in environmental pressures has been identified: increase in GHG emissions (despite a recent and temporary reduction from the economic recession), ground level ozone, increased used of mineral fertilizers, accelerated natural resource depletion and reduced biodiversity[19, 20].

What about the environmental pressures from waste management? Have they improved or worsened? Indicators seems to indicate a mixed answer: Increased quantity of waste, albeit at a reduced rate of growth in recent years, slight reduction in direct GHG emissions (significant drop in net greenhouse gas emissions[21]), increased methane recovery, reduced reliance on landfilling, increased quantity of packaging but higher recycling rate[20].

1.2 Increasing quantity of waste produced

In Europe, the overall quantity of waste reported for 2006 for EU27 was 2.95 billion tonnes of which an average 7% is household waste[22]. On a country basis, the proportion of household waste varies from 1% in Bulgaria to 46% in Latvia. In Denmark, household waste constitutes 14% of the total waste generated by the country. This shows a rather large diversity of waste types, and associated waste treatment. This variation depends on the level of construction and demolition waste, manufacturing waste and mining waste of each member state. For the same year (2006), municipal waste was 258 Mt (215 Mt for household waste only). Municipal waste is only a small portion of the total waste generated by society but it is certainly more challenging than other waste because of its multipoint source.

In terms of growth rate, the amounts of municipal solid waste have been increasing. In the European Union (EU27), a 15 % increase between 1995 and 2008 was observed with an annual increase of less than 1% since 2004, as opposed to 3% growth rate from 1995 to 1999[3]. In the Organisation for Economic Co-operation and Development (OECD) countries, an increase of 18 % has been reported between 1995 and 2007[4].

1.3 Increased complexity of waste types

Most of the new products being developed and marketed end up as a waste and need to be managed by the waste industry. The diversity of products and their resulting waste have increased significantly the complexity of waste types. A few generic examples are the substantial development of multilayer, and multimaterial packaging, the increased production of single use products, the creation of new polymers and additives, including biopolymers (made by living organisms), biodegradable polymers and biodegradable biopolymers, the recent increase of microtechnologies and nanomaterials, and finally new electronic waste. Curiously, very little specific research is carried out on these new materials to assess their environmental fate and how they affects existing waste management infrastructure, from an environmental liability point of view. The waste industry has to adapt to these new materials, necessitating the development of more diverse waste management technologies, since most, if not all, these new waste streams are potentially mixed with municipal waste.

1.4 Increased heterogeneity of waste

Composition of waste shows large differences within Europe and regionally, mainly related to the historical and cultural diversity of Europe. Figure 1-1 represents an illustrative summary of waste composition and is further discussed in Gentil *et al.* (III). The large disparity of waste composition might also be due to the lack of standardisation of waste characterisation. A number of waste characterisation methodologies have been proposed[23,24,25,26], but no compositional methodologies guidelines has yet been implemented at European level, despite efforts to harmonise data[27].

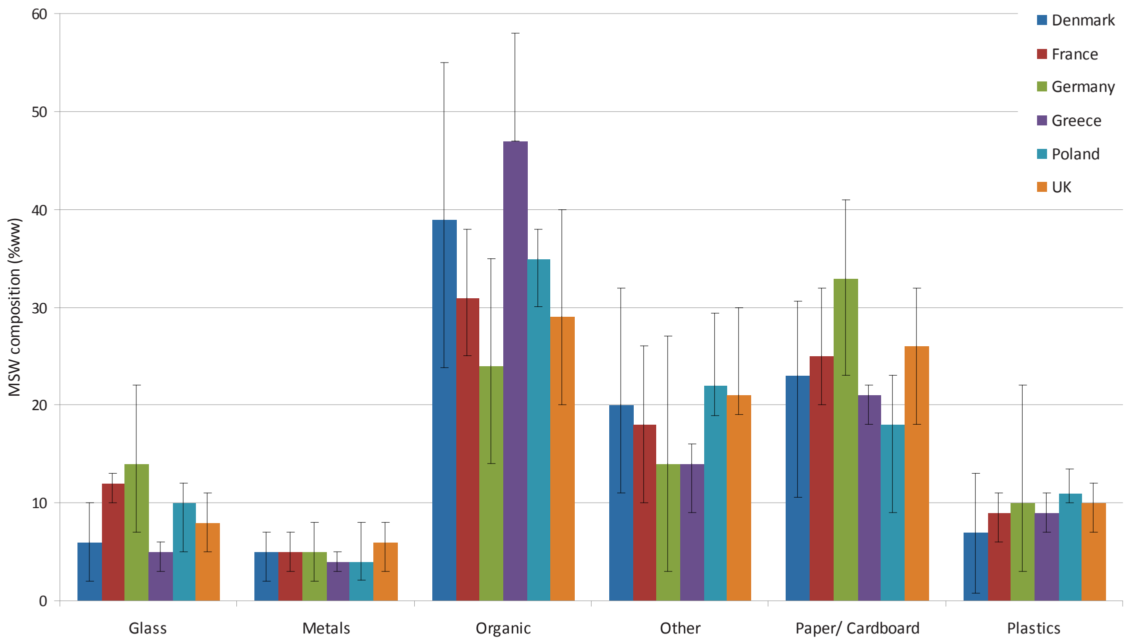

Figure 1-1. Variability of waste composition (Gentil, *et al.*, III)
Coloured bars represent the composition used in one of the studies presented in this study. Error bars represents compositional variability found in the literature.

Waste composition is probably the single most important parameter affecting the environmental performance of the waste management industry and as such, particular attention is needed to ensure the robustness of compositional data. This includes fractional and chemical composition. The latter is unlikely to vary significantly from year to year and from region to region, but the former is much more variable.

1.5 Increased complexity of waste management systems

In Europe, waste management activities have evolved from many relatively small and poorly controlled dumpsites to fewer, larger engineered landfill sites with a higher degree of environmental control[28,8]. Simultaneously, member states have invested in more advanced waste management infrastructure (recycling, biological treatment and incineration), reaching 70,189 plants in 2006 for EU27, subject to a waste management licence[29]. It is likely that these changes have been implemented for different reasons: European regulations, spatial constraints, capacity limits of existing infrastructure, national regulations, increased environmental pressures, NIMBY ("not in my back yard") and potentially the level of education on waste issues. Interestingly, but not surprisingly, this increased complexity has occurred at different pace in Europe, as indicated by the proportion of different waste management facilities[29].

To add to the complexity of the European waste management landscape, increased transboundary movement of waste has been reported. Movement of notified waste have evolved from 2.5 Mt (million tonnes) in 1997 to 8.3 Mt in 2003 for intra-boundaries movement[30,31]. This raises many questions about the assessment of the environmental performance of the waste management technologies in the receiving countries, located outside the EU. This is a commonly called "burden shifting" (delocalisation of the environmental impacts). Increased movement of waste outside the EU also affects treatment capacity within Europe.

In such a complex and contrasted waste management landscape, understanding the environmental implications of managing waste becomes a major challenge. Improving the environmental performance of existing infrastructures or waste management systems is probably even more challenging.

1.6 Increased regulatory regime for waste management

With the increased environmental pressures and complexity of waste related issues, come increased regulatory regimes. About 60 legal acts (regulations, directives, and decisions) related to waste are now in force, which arguably, acts as a strong driver for the diversification of the waste management landscape in the European Union. A comprehensive review of the legal instruments is out of the scope of this study. However, key regulatory procedures are presented to understand further the context of the research work.

1.6.1 Thematic strategies

Two overarching thematic strategies, namely, the Thematic Strategy on the prevention and recycling of waste[32] and the Thematic Strategy on the sustainable use of natural resources[33] have been produced to define the future waste management landscape from a regulatory angle. The fundamental objective of the Thematic Strategy on prevention and recycling of waste is to help Europe to become a “recycling society” through increased waste prevention and the transformation of waste to resources useful to society. The main objective of the Thematic Strategy on the sustainable use of natural resources is to reduce the environmental impacts of resources uses. These two interlinked European strategies have profound implications for the evolution of waste-related regulatory regime in Europe, as they are the driving forces behind the simplification and modernisation of existing waste legislation.

It is worth noting that these strategies have introduced life-cycle thinking into waste policy. This approach, which consists of evaluating and comparing the environmental impacts and benefits of a service or a product along its life cycle, is extensively used throughout the papers presented in this thesis.

1.6.2 Revised waste framework directive

Following the launch of the Thematic Strategies, a major development took place with the publication of the revised waste framework directive (Directive 2008/98/EC[34]). The key aspects, relevant to the context of this thesis, are presented below:

From waste hierarchy to life cycle thinking. One of the key aspects of the European framework directive is the implementation of the waste hierarchy as overarching priority guidance. However, a provision is included to move away from the hierarchy if it can be demonstrated that other waste management options are more favourable than what is prescribed by the hierarchy.

Waste prevention. One of the priorities of the directive, and the highest priority of the waste hierarchy, is to focus further and more practically on waste prevention with a requirement by the European Commission to provide guidelines and best practices examples, and for member states to submit waste prevention programmes.

Reuse, recycling and recovery of waste by targets. The directive prescribes targets to move further towards the "recycling society". By 2020, at least 50% (by weight) of paper, metal, plastic and glass from household waste shall be reused or recycled (the target is 70% for construction and demolition waste).

Clarification of the definition of waste. This includes the definition of by-product, which can be excluded from the scope of the directive if certain environmental and human health criteria and other conditions are met. End of waste criteria has also been defined to enable materials to be returned back in the economic cycle as a 'non-waste product' without being subject to waste management regulation.

Energy recovery criteria. The directive prescribes the minimum energy efficiency level (≥65%) for waste to energy plants that can be considered as an energy recovery activity.

With an increasing complexity of the waste landscape, more and more sophisticated computers models are required to understand the consequences of managing new waste and new technologies. Life-cycle thinking and LCA have emerged as being robust for the evaluation of the relative environmental consequences of waste management activities. The same methodology can also be extended to life-cycle costing[35,36] and more recently social LCA[37,38]. Other environmental assessment tools are reviewed in the literature[39,40,41]. Focus is here on the environmental assessment of waste management activities. LCA applied to waste management systems, or more commonly called "waste LCA", has been widely published in the literature [16,17] and many models have been developed over the years, generating further publications and sometimes inclusion of these models in the regulatory system in Europe[32,33] and in the UK[42]. It seems important, at this stage, to look further into a selection of waste specific tools available in order to get a better understanding of the technical assumptions made behind these models.

2 Waste LCA models

To address the increasing complexity of the waste management landscape, a number of waste LCA models have been developed, often independently from each others in different countries and at different moments in time. A review of waste LCA models was undertaken (Gentil *et al.*, I). This review included an assessment of the following models in alphabetical order: EASEWASTE, EPIC/CSR, IWM2, LCA-IWM, MSW-DST, ORWARE, SSWMSS, WISARD and WRATE.

Waste LCA tools have been developed over the years and therefore later models benefited from the lessons learnt from the earlier models. This is true both in terms of the number of validated datasets, comprehensiveness of these datasets and quality of the data.

The research has been supplemented with organisation of a workshop with the developers from Denmark (EASEWASTE), France (WISARD), Japan (SSWMSS), Sweden (ORWARE), the UK (WRATE) and the USA (MSW-DST). This meeting provided very valuable insight concerning the modelling assumptions and approaches used for the development of each model. Some of the findings are discussed in this section.

The subsequent analysis by Damgaard[43] showed the areas of differences between the models that could influence significantly the results. The focal point of this chapter is to learn from this exhaustive research work and to suggest a basis for the technical requirements and assumptions necessary for developing future waste LCA models.

This chapter is articulated in two main aspects. They include discussions on generic methodological aspects of waste LCA models and a description of the technical assumptions used for developing these models. Suggestions for future waste LCA model design are also provided.

2.1 Methodological aspects of waste LCA models

One of the findings from the model comparison exercise was that the tools have a different approach concerning generic issues, namely the assumptions concerning the time horizon (short or long), the energy system (marginal or average), carbon accounting and system boundaries.

2.1.1 Time horizon

It is well known and widely debated, that the choice of time horizon has a profound influence on the results and has different consequences on different impact categories.

The issue of time horizon, mainly for landfilling and land application of biotreated waste, has been debated for many years and no consensus has been achieved because both approaches (arbitrary surveyable of time of 100 years or near infinite timescale) are scientifically defensible. From a strict theoretical LCA methodology point of view, all emissions from the technosphere to the environment should be accounted for, regardless of the timeframe of their release[44,45]. The counter argument is that the uncertainty of long term leaching is so high due to the impossibility to measure leachate emissions and due to the sole reliance on probabilistic models, calibrated by laboratory column experiments, that it is preferable to include leachate emission over a surveyable period of 100 years with good certainty, while providing an indication of the potential contamination that remain in the landfill for an indefinite time[46]. Potential long term contamination has been addressed with the introduction of stored ecotoxicity[44]. Hauschild and colleagues also argued that accounting for total landfill emissions would provide unfair bias compared to other waste management technologies, since dilution in time would not be taken into account if all leachates releases are assumed to be immediate.

It is worth noting that recent probabilistic modelling have shown significant release of leachates to surface waters (overflow of the landfill) and through the landfill base (following the failure of landfill liner) between 600 and 1200 years after post-closure for household hazardous waste[47]. Similarly, long term emissions have been simulated, but with leachate column experiments[48]. Hycks and colleagues concluded that only 1% of the heavy metals are released in the first 100 years post-closure, out of a 10,000 years simulation.

The general message is that a waste LCA model should take into account long term emissions (beyond 100 years), whether one chooses potential leachate emissions with the stored toxicity method (estimated leachate composition and quantity in the first 100 years minus elemental composition of the incoming waste disposed to landfill), or estimated through risk assessment modelling. The most conservative approach (from the environmental point of view) would be to use stored toxicity, as it assumes that all chemical elements within a landfill, not released within the first 100 years post-closure, will be potentially discharged to the environment at some point in the future. The interpretation of the results for decision making is nonetheless difficult because it depends on whether long term emissions is valued equally or not, compared to instantaneous emissions and whether dilution in time should be assimilated to an instantaneous pulse. It is suggested that long term landfill emissions should be assessed through a scenario approach to aid the decision-making process, as opposed to using discounting for long term emissions. Hellweg argued that if a discounting rate is to be used, it should be equal to zero, meaning that future emissions have the same weight as present ones and therefore should be accounted for in LCA[45].

When the choice on the time horizon is predefined in the tool, different models with different assumption on time horizon will have significant differences, regardless any other parameters, as experienced when comparing the models. It is therefore suggested to ensure that waste LCA model allow the user to include a range of time horizons and present their results with short term and long term timescale. The problem is that the choice of time horizon is shifted from the developer to the users and this is likely to make decision making more difficult. The questions that will remain is whether long term emissions are an acceptable environmental risk that society is willing to take, and if long-term emissions are considered, what is the acceptable time horizon.

2.1.2 Energy system

It is widely acknowledged that the energy system has a strong influence on the results of waste LCA[49]. Many studies have discussed for or against the use of marginal electricity when modelling waste LCA. Most LCA practitioners would argue that it depends on the question asked. More clearly, it is suggested that the choice of energy mix (marginal or average) depends on the scale of the study and whether the study is a reporting or accounting exercise (attributional with the use of average mix) or a comparison between two systems (consequential with the use of marginal mix). If the scope is to study the environmental consequences of managing an additional tonne of waste, compared to an existing situation, then it makes sense to use marginal energy mix, since it is the marginal energy system that will be affected first by the marginal change in the waste management system. If, however, the scope of the study is the environmental consequence of managing waste for a region or a country, it can be argued that average energy mix (or a marginal mix close to the average mix) shall be used as a significant change if the waste management is likely to affect the whole energy system of the country under study. The main challenge is to evaluate the marginal mix[50].

Damgaard rightly argued that if marginal data is not available, that the use of average data is better than no information at all[43]. It can be further argued that if marginal data is not known precisely (marginal data change from year to year and from country to country, due partly to policy decisions and modernisation of technologies[50]), the modeller should use a scenario approach with the extreme range of likely marginal data. For instance, if it is known that the marginal energy system is likely to be dominated by coal, a valid approach could be to include a scenario with 100 % coal, likewise with a marginal assumed to be dominated by natural gas (Gentil *et al.*, III).

Interestingly, as European and global policies are driving slowly coal energy out of the energy mix, the marginal energy is likely to contain less and less coal from year to year[51]. In addition, a distinction is made between short-term marginal (a change that affects energy capacity utilisation) and a long-term marginal (a change that affects energy capacity utilisation and energy infrastructure)[52]. This is of particular importance for the modelling of waste LCA, where some choice of infrastructure are planned to last about 30 to 50 years. For example, it is likely that waste to energy plants (as all other waste management technologies) will be less environmentally beneficial in the long term future, compared to today, if one assumes that the energy system becomes less carbon intensive. Further aspects of this issue, although not directly related to waste LCA, have been discussed by Finnveden *et al.*[53].

In most waste management studies, the use of marginal energy is generally recommended. An essential support to the LCA community, and ultimately to the decision makers, would be to define a year by year marginal energy mix (heat and electricity) until 2050, provided by energy system analysis modellers, endorsed by national authorities and reviewed regularly with a statistical weight assigned to acknowledge the higher uncertainty in the future. In the mean time, LCA modellers should rely on using scenarios with different plausible marginal energies.

A waste LCA model should include the possibility for the user to decide which energy system assumption to be included in the study and whether the chosen energy system should be used throughout the study or for specific technologies within that study (there are cases where some waste management technologies interact with a specific external energy system, for recycling technologies, for instance).

2.1.3 Waste composition

In the waste LCA models reviewed, waste composition is usually defined by three levels of composition: primary waste fractions (paper, wood, plastic, ...), secondary waste fractions (newsprint, magazines, ...) and elemental composition (physical and chemical properties of the waste, such as lower heating value or mercury content of waste fractions). Not surprisingly, each model team has developed its own compositional data, based on available knowledge at the time of development of the model (Gentil *et al.*, I). Detailed waste composition is quite important, especially for waste specific emissions (mass balance between elemental composition of the incoming waste and the emissions from the waste management activity), where assumptions on any level of the waste composition will have a direct effects on the results. This is probably one of the parameters that distinguish between waste (system) LCA software (variable input waste composition is dynamically reflected in the results) and product LCA software (pre-determined waste composition generates a generic static emission inventory).

While primary and secondary waste fractions depends on the study undertaken (default and user entered information), it is unlikely that the user is expected to input information concerning the elemental composition, although this should be possible if the user has specific data.

The waste LCA model comparison work has raised some methodological and generic issues, described earlier. This exercise has also been essential in identifying a range of technical assumptions that will have various consequences on the results and comparability with other models.

2.2 Technical assumptions of waste LCA models

Gentil *et al.* (I) highlighted the various technical assumptions that have relevance for the results of the modelling. Basically, the technical assumptions of waste management LCA models can be summarised with a rather simplistic diagram (Figure 2-1) that might be evident for waste LCA practitioners but helpful for other potential users.

Figure 2-1 indicates that the choice of inputs parameters (ancillary product inputs, construction, maintenance, outputs of other processes...) will have a large influence on the results. Similarly, the type of technology (moving grate or fluidised bed incinerators), that include technical assumptions (transfer coefficients), specific to the technology chosen, will be determinant for the results. The breadth and depth of the LCIs that define the technology are directly linked to the breadth and depth of the calculated LCIs. This aspect is not always transparent in waste LCA models. Finally, the decision of what outputs are relevant to the study will also affect the results.

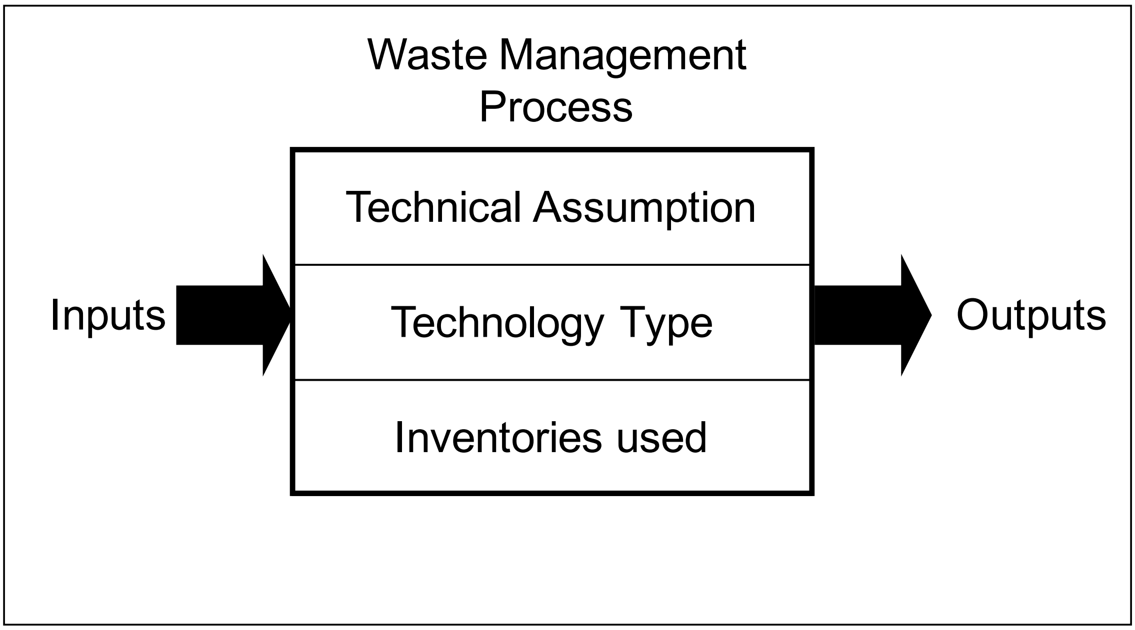

Figure 2-1. Generic waste technology in waste LCA (Gentil *et al.*, I)

In order to expect the same range of results when comparing different waste LCA models, all the parameters illustrated in Figure 2-1 need to be understood and be comparable. Different models with different results do not necessarily mean that one model is right and the other is wrong. It could just mean that the sets of parameters defining the system (and each underlying technology) are different between the different models. This was made particularly clear during the preparation of the workshops with the developers.

2.2.1 Input parameters

Input parameters, other than waste input, include ancillary materials (water, lime, activated carbon, fuel oil...) used by the process in order to treat the waste, while minimising emissions. Ideally, waste LCA models should calculate the quantity and type of ancillary materials based on waste specific and process specific information. Other inputs to waste treatment technologies also include construction (energy and construction material), maintenance (parts, filters, machinery) and decommission (energy use and use of equipment for decommissioning). With a strict reduction of emissions from waste incineration plants, the environmental impacts of treatment plants (construction, maintenance and decommission) become comparatively more important and therefore should probably be included in the assessment.

2.2.2 Technical assumptions of waste management technologies

Generic waste management technologies have been discussed in details in Gentil *et al.* (I). They include:

- collection and transport;
- intermediate facilities;
- material recycling;
- thermal treatment;
- biological treatment; and
- landfills.

2.2.2.1 Collection and transport

Two families of models were identified: mechanistic and deterministic. Mechanistic models are usually defined by large number of user-defined input parameters used to calculate the total distance and fuel consumption of the vehicles in the waste management system. Deterministic models use only the total distance and fuel consumption entered by the user. In fact the intermediary output of the mechanistic models could be used as input parameters to the more simple models.

Three key parameters are of importance in collection and transport: fuel type, consumption and emissions. Obviously the consumption and emissions depends on many secondary parameters: road types, driving behaviour, level of urbanisation. To keep waste LCA modelling to a relatively simple level, it is recommended that collection and transportation calculations are performed as a separate module, where the outputs of that module are used as input to the waste LCA model. The alternative is to use default data from the waste LCA model. A good approach is to use vehicles emission standards (in Europe, EURO 1 to 6) and integrate it to the waste LCA model. While collection and transport weighs relatively little when studying a full waste management system[54], it might prove much more important as source-separated collection systems are developed further or if the study is focused on the environmental optimisation of collection and transport.

2.2.2.2 Intermediate facilities

Intermediate facilities (transfer stations, material recovery facilities and recycling banks) are relatively simple processes that have little direct emissions. The environmental performance of such facilities depends mainly on energy consumption (from the various machines used), quantity and composition of rejects (facilities with small reject levels have a higher performance). Proportionally they have higher environmental capital cost (construction) per tonne of material managed, than other waste management facilities.

2.2.2.3 Recycling technologies

The modelling of recycling technologies is performed in a relatively simple way in waste LCA models. This is probably for this reason that very little difference has been observed among the different models reviewed[43]. One of the key challenges of this technology group is to define the system boundaries (*i.e.* what constitutes part of the waste management system, what constitutes part of the industrial system). Recycling modelling in waste LCA calculates the environmental loads of the recycling activity. This usually includes emissions from machinery usage, intermodal transport and rejects, which are different between the different materials recycled. Based on the quantity of material recovered in the recycling process, an amount of virgin production emissions is then subtracted (substituted). Obviously, a substitution ratio<1 should be applied to take into consideration loss of quantity (rejects) and loss of quality (shortened cellulosic fibres in paper recycling) in the recycling supply chain. The substitution ratio is probably the most important and most difficult parameter to define for recycling technologies. For this reason, this ratio should be clearly available as default and editable to the waste LCA practitioner. Further, the choice of ratio should preferentially be substantiated, as it could be determinant for the results. Failing that, it is recommended to undertake sensitivity analyses with a range of substitution ratios.

The recycling modelling from a consequential perspective is far more complex to perform. It requires significant work to identify the marginal technology that will be substituted when an additional tonne of recycling is achieved in the waste management system. The choice of substituted technology has shown to have a great influence on LCA results[55]. Identifying marginal technology requires the evaluation of market elasticities, using input-output analysis, which changes on a daily basis and where the market is global by nature[56].

This is why no model in the review currently includes marginal recycling technology defaults, although this could be easily implemented from new studies or circumvented by using scenario comparison. Once a marginal technology (or more precisely a mix of marginal technologies) is identified, further challenges remains: identification of the ratio of recycling/virgin material used in the substituted manufacturing process (higher ratio indicates a reduction in the recycling benefits credited to the waste management system) and the environmental performance of the marginal technology (a substituted technology, located in a country with a high carbon energy mix, will have a higher environmental load, increasing the benefits credited to the waste management system, if one gets the assurance that the material is actually recycled in marketable products.

The final issue is whether the recovered material will be subject to a closed-loop recycling, open-loop recycling or downcycling, with and without rebound effect. How these aspects should be addressed in future waste LCA models has been debated widely but its practical implementation is not yet clear.

2.2.2.4 Biotreatment

This technology group includes aerobic composting, anaerobic digestion and mechanical biological treatment (a mix of both technologies with various levels of separation). The LCA modelling of biotreatment consists usually of two modules: a biotreatment technology and a use-on-land module, because the environmental performance of biotreatment is inherently linked to the performance of its products (compost, digestate). The environmental performance of these products is also affected by the type of land application. Different technical assumptions have been noted between different models, especially concerning system boundaries and level of details for the use on land of the biotreated materials[57,58]. Some models calculate the biotreated material composition based on the input waste composition, other use generic compost composition. In order to determine the potential benefits of biotreated materials (substitution of inorganic fertilizers), it is recommended to include waste specific parameters such as C, N, P, and K in its composition. Heavy metals content in the biotreated product should also be waste specific. A transfer coefficient matrix, where the different outputs of the biotreatment process are distributed to different environmental compartments and biotreated products, are also very important, in order ensure mass balance between input and outputs.

There are a number of important parameters to consider in the LCA modelling of biotreatment:

- gaseous emissions (NH3, N2O, CH4);
- removal / attenuation efficiency matrix (for the treatment of gaseous emissions and leachate emissions);

- methane recovery;
- carbon binding in the biotreated material after application to land;
- choice of substituted materials (inorganic fertilizers, peat, straw, ...); and
- level of reject at the treatment plant.

2.2.2.5 Thermal treatment

Thermal treatments (incineration, gasification, pyrolysis and autoclaving) are quite complex technologies that include many input, operating and output parameters that are all interrelated. The level of complexity used in the models are different between different types of technologies and between different types of waste LCA models (Gentil *et al.*, I). Based on the model review process and available literature, emissions of thermal treatment plants are usually based on waste specific emissions (emissions depends on the elemental waste composition) and process specific emissions (emissions depends on the quantity of waste treated and the air pollution control in place). To ensure a rigorous elemental mass balance between input waste and emissions and an appropriate apportioning of emissions to different environmental compartments, it is critical to define a matrix of transfer coefficients[59]. The definition of thermal treatment parameters used in a waste LCA is fairly well known and easily replicable[60,61]. The scientific and technical debate is to define and agree on suitable transfer coefficients, knowing that they are affected by the waste composition and the type of technology used.

To this extent, EASEWASTE, based on the work of Kirkeby *et al.*[61] and Riber[59], provides comprehensive, scientifically robust and user editable thermal treatment datasets (user with more specific data can use their own transfer coefficients). Additional parameters/information relevant to future waste LCA models could include: display of the lower heating value of the waste before treatment, calculated ancillary materials based on the waste composition, display of energy produced in GJ.tonne^{-1} of waste (heat, electricity), user entered limit value on specific pollutants (emissions reaching limit values could trigger a new display with the relevant information).

2.2.2.6 Landfill

Landfill is probably the most widely researched waste management technology since it is the oldest and probably the least controlled. Time horizon has been discussed earlier (section 2.1.1) and is considered the single most important parameter affecting the results (Gentil *et al.*, I). Process specific parameters affecting the environmental performance are:

- gas collection efficiency (averaged over a pre-defined time horizon, usually 100 years);
- landfill gas utilisation (% used for energy recovery, % flared);
- top cover methane oxidation; and
- removal efficiency factors of leachate treatment plant and sludge management;

Obviously the environmental performance of landfills also depends on many other site specific parameters such as landfill configuration, bottom and top lining system, and rain water ingress.

The definition of all the technology groups described above requires significant efforts due to the complexity of the technologies, because of the dynamic nature of these technologies and the multi-input-multi-output challenges that represent most waste management technologies. Fortunately, a significant amount of predefined technologies populates the databases of most waste LCA models with a varying degree of complexity. Technologies databases (foreground data) should not be confused with life cycle inventory (LCI) databases (background or terminated processes). Technology databases include parameters that define industrial processes, LCI databases are the environmental outputs of a process.

The WRATE developers have designed and built what is probably the most exhaustive database of waste management technologies available today. However, the database is proprietary (the revenues are used to further develop the tool and expand the technology database), and mostly adapted to the UK situation. In contrast, EASEWASTE, the Danish model, includes less waste management technologies in its database but all its technologies have been rigorously researched with measurements, calibration of the data, often with the support of the industry and ultimately published in peer-reviewed literature.

2.2.3 Comprehensiveness of LCI

All LCIs used from external databases or calculated by the models include a variable number of emissions that can be used in the same model (different data source, data availability). This is an inherent limitation of LCA where processes with a high number of emissions could potentially have higher impacts, simply because of the number of emissions included. Some have addressed this issue by using the smallest number of tracked emissions across all the different technologies: information is lost but different technologies are more fairly represented (MSW-DST model). Others have been using complete datasets on the basis that more comprehensive data represent more realistically the processes modelled, despite inconsistencies between processes. Current practices would indicate that it is preferable to keep as much data as available.

A logical development for future improvement, increased scientific robustness and better transparency, could be to flag emissions not reported uniformly across all the modelled processes (and individual LCIs within the same analysis) to enable the user to assess the importance of the missing data. Since a number of emissions reported in LCIs are not characterised by any current life cycle impact assessment methodologies, it could also be useful to highlight uncharacterised LCI data. This is probably becoming an important feature as LCA models and LCI databases are more and more detailed.

2.3 Suggestions for waste LCA model design

2.3.1 Standardised waste composition

The importance of waste composition has been emphasised earlier (2.1.3). One of the problems with waste LCA models lies on the lack of standardisation of waste definition, which makes comparison using different models rather difficult, as shown in Gentil *et al.* (I). Future waste LCA should include:

- a standard codification of waste types (the European list of waste is a good example[62]);
- a waste composition matrix (primary, secondary fractions and elemental composition), using waste characterisation analysis; and
- a comparability matrix (USA/EU for example).

Based on the experience from the model comparison exercise, waste characterisation literature[63] and various discussions, a number of composition parameters deemed important for the development of waste LCA modelling are suggested in Table 2-1.

It seems important to develop existing compositional databases to include elemental composition of waste electrical and electronic equipment (WEEE), present in the residual waste and collected separately, although much more characterisation work would be needed. This is obviously an extremely tedious task but could be initiated with the most precious elements (gold, silver, and palladium), the most toxic elements (mercury, tin) and the highest abiotic depletion potential (beryllium, indium). Common household hazardous waste should also be characterised (paint, solvents, pesticides, cleaning agents). Persistent organic pollutants (POPs), such as bisphenol A and polychlorobyphenyls are much more difficult to characterise because of their inferred very low concentration in municipal waste, their largely unknown waste.

Table 2-1. Potential waste composition parameters for waste LCA models

Parameter type	Parameter name
Chemical parameters	Al, As, Br, C, Ca, Cd, Cl, Cr, Cu, F, Fe, H, Hg, K, Mg, Mn, Mo, N, Na, Ni, O, P, Pb, S, Sb, Sn, Ti, Zn
Physical parameters	Total solids (TS), Volatile solid (VS), water content, lower heating value (LHV)
Carbon parameters	Total carbon content, biogenic carbon, fossil carbon, C_{bio}/C_{foss} ratio, degradable carbon, methane potential, ash content
Waste electrical and electronic equipment	Ag, Au, Pd, Pt, V (precious metals) Be, In (high abiotic depletion)
Household hazardous waste	Paint (As), solvents (toluene), pesticides (pyrethroid), cleaning agents (detergent, surfactants)
Persistent organic pollutants	Bisphenol A, polychlorobyphenyls

management pathways and chemical properties modifications during waste treatment. However, the levels of POPs in waste is subject to new European regulations (Commission Regulations 756/2010/EU[64] and 757/2010/EU[65]), which should be a driver for implementation in waste LCA models.

It is expected that modern waste LCA models are structured to accommodate for newer waste composition, despite the current lack of data.

2.3.2 Energy system in future waste LCA models

From the earlier discussions in section 2.1.2, energy modelling plays an essential role in waste LCA modelling and therefore energy assumptions should be presented very clearly to the users, who are usually not specialised in energy modelling. Some suggestions for improvement to existing models include:

- definition of energy system for the whole study or for specific technologies;
- choice between marginal and average energy sources;
- choice between short term and long term marginals;
- evaluation of the uncertainty of the chosen energy system;

- percentage proportion of energy sources used in the model/technology;
- choice of transmission loss (% or high, medium, low);
- choice of energy production efficiency (electricity and heat);
- provision of new energy sources LCIs (wind, biomass, hydro, geothermal);
- availability of default marginal energy mix datasets (country and year dependent); and
- possibility to include the output data of an energy system analysis as input data for waste LCA models.

2.3.3 Other issues to consider in waste LCA model design

The development of new waste LCA models could include:

Visual interface of system boundaries. This could include the waste management, energy, forestry and industry systems. While this would not change the modelling capability of the tool, it would provide support to non-LCA experts.

Object-based modelling. Use of visual objects linked to data of varying complexity could help the practitioner to define large waste management systems.

Tabular results presentation. Presentation of the results using the UOD approach, as presented in Gentil *et al.* (II), would improve the transparency and communicability of the LCA results.

Time series modelling. This aspect is currently missing in current models but obviously can be performed manually. Time series modelling implies that the model is run repeatedly over a number of years or months, with different user entered parameters (fixed and variable waste quantity, change in energy mix with time). This could prove highly valuable for target setting and choice of waste management infrastructure, particularly for local authorities relying on landfills.

The review of the waste LCA models has shown that differences in the models depends on a choice of technical assumptions and their associated data, which will lead to a difference in the results when using the same input data. However, no calculation inconsistencies have been identified, indicating a good level of robustness for each of the models[43]. All LCA models reviewed integrate a number of environmental pressures, based on the use of life cycle impact assessment characterisation methodologies. Among the different methodologies, global warming potential (GWP) is used systematically in all the models reviewed. GWP is also used in a number of other reporting and modelling mechanisms. However, the calculation of GHG and their associated GWP can be quite different, due principally to their different scope.

3 Waste management and climate change

Anthropogenic global warming is arguably one of the most serious environmental impacts because of its global scale and because its severity is increasing, with a strong potential for affecting humanity[18]. Based on these widely reported and peer reviewed findings, it seems natural to address AGW in the context of the waste management industry and evaluate existing knowledge on this issue.

It is worth noting that 50% of Annex 1 countries under the Kyoto Protocol, have reportedly decreased their aggregate greenhouse gas emissions between 1990 and 2008 for the waste sector[10]. While AGW has recently received a great deal of attention in the general public, the LCA community has been working for a number of years on the subject, in association with a number of other environmental pressures.

This chapter focuses first on the different methodologies used for accounting, reporting and modelling GWP (Gentil *et al.*, II). In a second part, an evaluation of the global warming factor (GWF) is presented with emphasis on the waste management performance of Denmark, France, Germany, Greece, Poland and the United Kingdom (Gentil *et al.*, III).

Much of the research work undertaken in this section has been closely associated with a number of wider projects that included a technical review on climate change and waste management, contribution in three workshops organised by the International Solid Waste Association (ISWA) and the publication of an industry-wide white paper, describing the potential GHG sources and technical solutions towards GHG mitigation.

3.1 GHG accounting and waste management

A general background information concerning AGW and waste management that includes the physical phenomenon of the greenhouse effects (radiative forcing, GWP) has been provided by Scheutz *et al.*[66]. It was concluded that there is still a significant uncertainty concerning the quantification of direct operating emissions from the waste industry because of its inherent diversity of point sources and fugitive emissions, and also due to the delayed emissions of landfills and composting facilities, estimated through modelling. The estimation of the potential benefit of waste management is performed only through modelling and therefore is also uncertain to some extent.

3.1.1 Upstream-Operating-Downstream framework

The accounting, reporting and modelling of greenhouse gas emissions started to be implemented on a global scale since the inception of the Kyoto Protocol, back in 1997 and earlier for some countries. With this protocol in place, ratified and signed by 187 states, a number of reporting protocols have been developed to enable the quantification of anthropogenic GHG emissions. Some of these accounting frameworks have been developed especially the waste management activities. These accounting mechanisms includes principally the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[67], the Protocol for the Quantification of Greenhouse Gases Emissions from Waste Management Activities or the EpE protocol[68] and the trading mechanisms (clean development mechanisms methodologies).

All these major protocols were reviewed in Gentil *et al.* (II) and were assessed alongside waste LCA methodology, which also quantifies GHG emissions. This analysis indicated that all these procedures were including the same basic data from waste management activities (obviously amalgamated at different levels). The review also showed that the level of inclusiveness of these data, along the waste supply chain, was different depending on the reporting methodology and could lead to confusion for waste management stakeholders.

It is important to clarify that these protocols could be summarised in two overall and distinct aspects that include:

- GHG emissions reporting, partly based on historical data (landfills) and current annual emission data (IPCC, EpE protocol); and
- prospective modelling, based on existing data and modelled predictions (LCA modelling to evaluate the potential future consequences of decisions made today and CDM methodologies).

The most important outcome of the paper was to suggest a generic framework that could encompass the different mechanisms without altering or replacing existing methodologies (Gentil *et al.*, II). The proposed generic framework, called the upstream-operating-downstream (UOD) framework is a very simple reporting mechanism, based on a supply chain model, where information specific to the accounting scope can be viewed and selected by the user. The UOD framework and its relationship with the different mechanisms are illustrated in Table 3-1.

Table 3-1. GHG accounting mechanisms and UOD framework (Gentil, *et al.*, II)

Waste Composition	Energy Mix

Process specific GHG inventory (per tonne of waste)		
Indirect: Upstream	**Direct: Operating Waste Management**	**Indirect: Downstream**
GWP_{100} CO_2-eq.	GWP_{100} CO_2-eq.	GWP_{100} CO_2-eq.
Accounted	Accounted	Accounted
Not Accounted	Not Accounted	Not Accounted

GHG Accounting and Reporting Mechanisms			
Trading Schemes	**Life Cycle Assessment**	**Organisation Accounting**	**National Accounting**
• CDM • JI • EU-ETS • CCX • JVETS • Others	• ISO14048 • LCI Databases: -Ecoinvent -ELCD -GEMIS -Others • LCA models: -WRATE -DST -EASEWASTE -Others	• ISO14064 • WRI/WBCSD • EpE • ICLEI • GRI	• IPCC Guidelines • CLRTAP • EPER / PRTR • CORINAIR • National Registries • UNFCCC
Role and Contribution of Waste Management			
• Cap and Trade • CER, ERU, AAU • Tech Transfer	• Decision Support • Strategy • Planning	• Benchmarking • Goal setting • Annual report • Sustainability report • CSR report	• IPCC AR • COP
Driving Policy Change, sustainable decisions, innovation, financing...			

AAU: Assigned Allowance Unites, **AR**: Assessment Report, **CCX**: Chicago Climate Exchange, **CER**: Certified Emissions Reductions, **CDM**: Clean Development Mechanism, **CLRTAP**: Convention on Long-Range Transboundary Air Pollution, **COP**: Conference of the Parties, **CORINAIR**: Core Inventory of Air Emissions, **CSR**: Corporate social responsibility, **ELCD**: European Reference Life Cycle Data System, **EpE**: Entreprises pour l'Environnement, **EPER**: European Pollutant Emission Register, **ERU**: Emission Reduction Units, **EU-ETS**: European Emissions Trading Scheme, **GEMIS**: Global Emission Model of Integrated Systems, **GHG**: Greenhouse gases, **GRI**: Global Reporting Initiative, **ICLEI**: International Council for Local Environmental Initiatives, **IPCC**: Intergovernmental Panel on Climate Change, **IPCC AR**: IPCC Assessment Report, **JI**: Joint Implementation, **JVETS**: Japan's Voluntary Emissions Trading Scheme, **LCI**: Life cycle assessment, **PRTR**: Pollutant Release and Transfer Registers, **UNFCCC**: United Nations Framework Convention on Climate Change, **WBCSD**: World Business Council for Sustainable Development, **WRI**: World Resources Institute.

The UOD framework is based on the fact that all waste management activities have upstream activities, with their associated environmental impacts, needed for running waste management operations (fuel, ancillary materials, construction, ...). All these waste management operations have their own emissions and finally, recovered materials and energy from these operations can be supplied back to the economic cycle, offsetting primary resources, with a potential environmental gain.

While this supply chain approach has been widely used by the LCA community, the other mechanisms have focused mainly on the direct operating emissions, probably because, historically, the waste management industry was broadly constituted of disposal (open dumping, landfilling) and mass burn incineration, without energy recovery. The EpE protocol, industry led and partially based on the WRI/WBCSD protocol, is an exception to this, where it has included upstream and downstream activities, using emissions factors.

Another reason why upstream and downstream activities have not been reported is because it is claimed that these activities are accounted for in other sectors (energy, forestry, industry) and therefore including them would lead to double counting. This is possibly true, although it can be argued that there is nothing wrong in double counting in this context, providing that transparency remains in the reporting. It could actually be a useful additional quality control indicator to evaluate whether data from other sectors are adequately reported. This is why it is believed that the UOD could provide a useful reporting framework.

The proposed UOD framework should be read from two angles: the different columns represent the different levels within the waste management supply chain (upstream, operating downstream). The different rows represent different levels of aggregation of GHG emissions, the highest row representing the total potential impact, expressed in CO_2-eq, the middle row indicating the emissions, or avoided emissions, of individual GHG, and finally the bottom row shows the activities / emissions that are not reported (due to data unavailability) to ensure reporting transparency between different waste management systems (Gentil *et al.*, II).

3.1.2 General rules used in the UOD

The UOD framework is a simple concept, aiming to support reporting consistency and transparency (what GHG is being reported, how much and where it belongs to within the waste supply chain). Despite its simplicity, it is important to summarise the overarching rules necessary for its implementation. They include:

- quantification of flows for each GHG reported;
- provision of the GWP/GWF (amalgamated) only in the top row;
- upstream: left column, materials & energy used by waste management;
- operating: central column, reporting entity (activity);
- downstream: right column: materials and energy recovered;
- unaccounted row can be “upgraded“ to accounted row;
- vertical columns can never be mixed (to keep transparency);
- GWP reference should always be defined with emission time horizon;
- UOD table content depends on the technology, country and year; and
- the time horizon range of waste managed (Start date, reporting date, historical data or prospective modelling).

3.1.3 Parameters influencing GHG accounting

While GHG accounting is reported under different scope (whether for annual reporting or for prospective modelling), a number of parameters play a critical role, namely the understanding and underlying assumptions concerning the carbon cycle, the time horizon of carbon in waste management and the actual metric used to calculate the strengths of the emitted GHG.

3.1.3.1 Carbon cycle

An essential component of GHG accounting, reporting and modelling is related to the carbon cycle within the waste management system. This issue has been widely discussed in the literature, with often conflicting interpretation. The debate has been revolving around the type of carbon managed by the waste management industry: should biogenic carbon (atmospheric carbon absorbed recently by the biosphere) and fossil carbon (atmospheric carbon absorbed during geological time and released within the last 200 years) have the same impact on AGW? What about the sequestration of carbon in landfills, is there any difference between fossil and biogenic sources of carbon? The different views on carbon accounting have been integrated and compiled in a simple carbon cycle model and tested through a number of scenarios to evaluate their validity[69]. Christensen and colleagues[69] identified that two sets of scenario out of four were mathematically consistent for the ranking of waste management technologies. These two scenarios are presented in Table 3-2.

Table 3-2. Factors for biogenic and fossil carbon

	Biogenic	Fossil
Air emission	0/1	1/1
C binding	-1*/0	0/0

C binding is assumed for 100 years after disposal. Constant forestry stock assumed. *to be multiplied by 44/12 to obtain CO_2-eq.

The global warming factor, or GWF, was introduced to differentiate between the different types of carbon and their different impact on climate change. For the remaining of this section, the following has been assumed:

- GWF [CO2bio] emitted = GWP100 [CO2] x 0 = 0 CO2-eq
- GWF [CH4bio] emitted = GWP100[CH4] CO2-eq*
- GWF [Cfoss] emitted = GWP100[GHG] x 1= GWP100[GHG] CO2-eq
- GWF [Cbio] bound = Cbio x -1 x 44/12 CO2-eq
- GWF [Cfoss] bound = 0 CO2-eq

*In reality, GWF [CH_{4bio}] emitted = $GWP_{100}[CH_4]-1$ CO_2-eq to differentiate between biogenic and fossil methane emissions[70]. However, this was not taken into account in the modelling.

3.1.3.2 Time horizon

Time horizon has been discussed extensively earlier (2.1.3) but it has a specific importance in the context of climate change and waste management. It seems that there is a degree of confusion concerning this issue. In waste management, and more precisely for landfill and application of bio-treated waste to land, two different types of time horizon are used:

- GHG emissions emitted from one unit of waste landfilled (100-150 years); and
- Impact potential once the GHGs have been released to the atmosphere (20, 100 or 500 years).

In other words, each molecule of methane emitted from the landfill has an (arbitrary) impact over 100 years with the last molecule of methane released 150 years after the waste has been disposed.

Depending on the accounting scope, landfill emissions are calculated based on the historical waste input quantity and composition (IPCC guidelines, corporate reporting). In contrast, in waste LCA methodology, it is usually assumed that waste disposed within the scope of the study has no historical emission, as we are interested in the consequences of the waste disposed today and its associated future emissions. This means that the two accounting scopes and the data are not comparable.

Other time related questions remain such as whether there is a climate benefit of delayed emissions from landfills and if so, how we should integrate it to the LCA methodology. This could have major implication for the choice of landfill technologies.

3.1.4 Update on the GWP

Boucher *et al.*[70] indicated that oxidation of methane into carbon dioxide was not appropriately accounted for and suggested that fossil methane should have a higher GWP_{100} compared to the IPCC Fourth Assessment report[71] (27 to 28 as opposed to 25). For biogenic methane, the authors recommend GWP_{100} of 26 or 27.

Shindell *et al.*[72] have calculated a much larger GWP with a much larger uncertainty, using a different technique. They indicated that when GWP calculation includes direct and indirect aerosols that the GWP_{100} of methane is ranging between 25 and 40. This new knowledge has profound consequences on the waste management industry. While the international reporting protocols use the reference system of the IPCC Second Assessment Report (GWP_{100}, $CH_4=21CO_2$) for time series comparison purposes, this does give a false sense of reality. It is therefore suggested to include the lower band and the higher band estimate of GWP when using this indicator. Using a range of GWP would be most helpful to policy makers since decisions could be drafted based on current knowledge rather than current (underestimated) national inventory reports.

The alternative is to use another metric than GWP. Some authors have suggested that global temperature change potential (GTP) could be a better alternative than GWP, because it integrates a change of global temperature at a given time, following GHG emissions, which seems to be more easily understood by policy makers and potentially other waste management stakeholders[73]. This metric also addresses some of the shortfalls of the GWP, despite a higher uncertainty. This is relevant to the waste management industry (more specifically for policy and research) since this metric will probably be used in future IPCC assessment reports. It is difficult at this stage to evaluate whether this new metric will affect the waste industry, but one thing is certain: emissions of methane will still have strong impact on climate change (whether GWP or GTP is employed) and simultaneously, mitigation of methane emissions through engineered waste management (with energy and material recovery) will continue to brings significant environmental benefits to the waste industry and wider society.

3.2 Global warming factor performance in Europe

The review of the different methodologies has shown that the GHG accounting can be performed for different objectives, whether it is for emission reporting at the national level, based partly on historical waste disposal (IPCC, corporate reporting), or for prospective studies to compare and evaluate the future GHG emissions of waste management decisions made at a given time (LCA and to some extent CDM methodology). As a practical application of prospective study, a waste management performance comparison has been performed on six European member states using life cycle thinking and restricted to the assessment of global warming potential (Gentil *et al.*, III). The study focuses on the environmental consequences (present and future) of municipal waste managed in 2007 and excludes historical waste management prior to that date and future waste management activities after that date.

This type of study provides an insight on current waste management performance from a national perspective, which could be used to support evidence-based policy at the European level. This study should be, however, distinguished from other national assessment comparison, such as the policy work undertaken by the European Environment Agency (EEA), which analysed time series of waste management performance, and included historical landfill emissions and future waste production prognosis.

3.2.1 Representative member states

In order to gain an understanding of the global warming performance of waste management in Europe, it was important to select a small, but representative, number of member states with radically different national waste management practices.

European member states (MS) were selected based on their overall waste management characteristics and included Denmark (DK), France (FR), Germany (DE), Greece (GR), Poland (PL) and the United Kingdom (UK).

The main reasons for the choice of MS are summarised below:

- **Denmark**: high reliance on energy from waste, landfill ban;
- **France**: balance between recycling, energy from waste and landfilling;
- **Germany**: high energy from waste, high level of recycling, good level of biotreatment and landfill ban;
- **Greece**: high reliance on landfill with restricted landfill gas recovery;
- **Poland**: high reliance on landfill and energy mix based on brown coal; and
- **The UK**: high reliance on highly efficient landfills and some recycling.

The major limitation when undertaking a country level assessment is the reliance on national statistical data that, by definition, removes site specific and regional waste management knowledge. However, it is believed that this can be useful for the development of stronger evidence-based policy as it highlights the differences of environmental performance between member states, but more importantly, it can help to understand why these differences exist and learn what can be improved with existing infrastructure, by sharing knowledge between member states.

3.2.2 Modelling assumptions

The system boundaries include exchanges with forestry (paper and card recycling), industry (glass, plastic, aluminium, ferrous materials recycling) and energy systems (heat and electricity substitution), however it excludes cascading effect. For instance, excess wood due to paper recycling, used for energy production has not been modelled in this particular paper.

As indicated earlier (section 2.1.3), waste composition plays a critical role on waste LCA modelling. It is therefore important to obtain robust data. Unfortunately, there is currently no standardised method and therefore no European statistics on waste composition. Compositional data was computed from the literature in order to define MS specific composition. A summary of the composition is presented in Table 3-3.

Table 3-3. Waste composition estimated for 6 member states in 2007.

Waste composition (% of MSW)	DK	FR	DE	GR	PL	UK
Paper	23	25	33	21	18	26
Others	20	18	14	14	22	21
Kitchen waste	19	19	13	41	28	15
Garden sep	18	10	10	2	4	12
Plastics	7	9	10	9	11	10
Glass	6	12	14	5	10	8
Metal	5	5	5	4	4	6
Garden non-sep.	2	2	1	4	3	2

Another key methodological approach to this kind of country wide analysis is to better understand the technology parameters that are likely to affect the results significantly. Parameters were defined for collection and transport, incineration, landfill, MBT and recycling.

Some parameters rely on assumption when no sufficient data is available. All the key technology parameters are presented in Gentil *et al.* (III) and are summarised in Table 3-4.

Table 3-4. Key parameters affecting the GWF performance of waste management

Technology type	Significant parameter
Collection & transport	Insignificant contribution
Recycling	Substitution ratio
Mechanical biological treatment	Energy recovery of refuse derived fuel
Incineration	• Electricity and heat efficiency of the plant • Lower heating value of the waste • Fossil carbon content of the waste
Landfill	• Landfill gas collection rate • Landfill gas utilisation rate • Landfill gas oxidation rate

It is obvious that the parameters presented in Table 3-4 are far from being exhaustive and many other parameters are required for a wider analysis that include other environmental aspects, as it is the case in a full LCA.

The generic waste management model is described in Figure 3-1. It includes the respective waste composition of each MS, defined in Table 3-3 and the national proportion of waste management technologies, reported by Eurostat waste statistics. The environmental assessment was performed with the use of waste management technologies from the EASEWASTE waste LCA model. The choice of the technologies was made based on the main types of technologies used by each MS and key parameters (Table 3-4) applied to these generic waste management technologies. This included waste generated by household recovered at source (composting and recycling) and residuals waste (landfill, incineration, MBT).

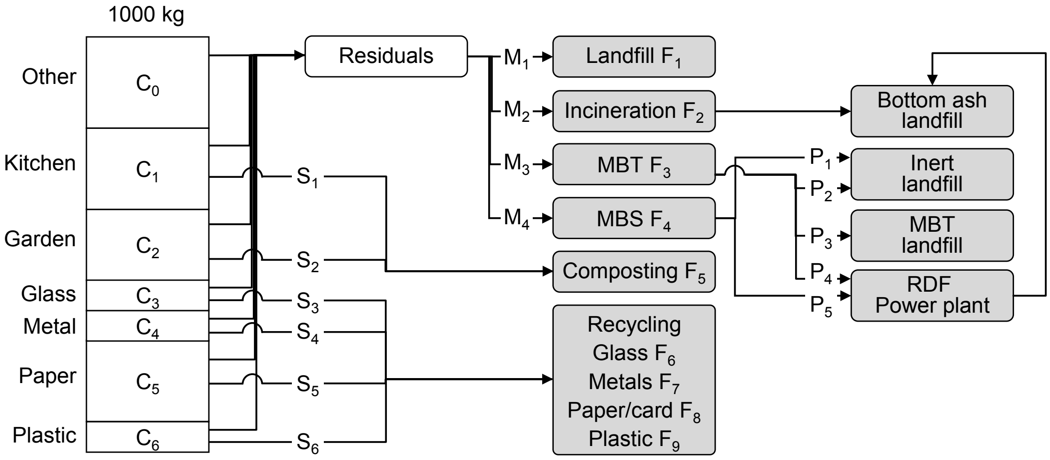

Figure 3-1. Generic flow diagram of the European waste management system (Gentil *et al.*, III)

3.2.3 Outcome of the study

When all scenarios are completed and the flows of waste mass-balanced, for each member state, the LCA modelling is then performed. Results are shown in Figure 3-2 and include the combination of upstream, operating and downstream loads and benefits. The figure represents the environmental performance calculated for Denmark, France, Germany, Greece, Poland and the UK. Figure 3-2 (a), (b), and (c) shows the GWF performance on a tonne of wet waste, per inhabitant and total MS emissions, respectively. The number in bracket under each MS label represents the quantity of MSW generated by inhabitant (b) and the total quantity of MSW produced by the MS in million tonnes (c), based on statistical data from Eurostat[74].

For each MS, the waste management system was modelled with their respective average energy mix and subsequently remodelled with 100% natural gas substitution and 100 % coal substitution. The reasoning behind this approach is that the determination of marginal energy is quite uncertain. Based on the current mix and current marginal electricity in Europe, it is highly likely that the marginal is dominated by natural gas or by coal and, most probably, the true marginal is a mix of different energy sources on a national level, with increasing new unconstrained sources, such as wind power[50] (not modelled here).

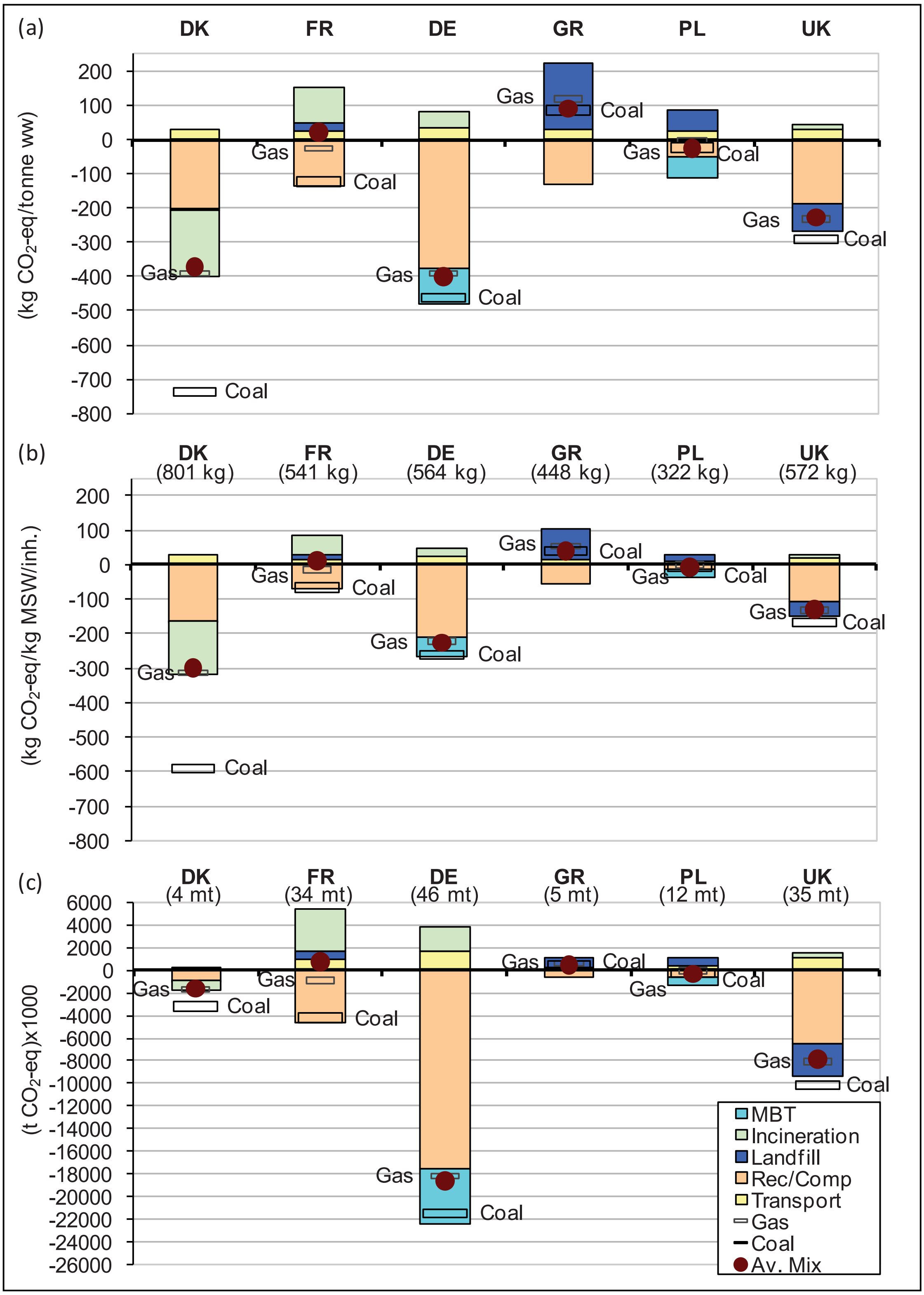

Figure 3-2. GWF for the national waste management of 6 European member states Positive values indicate a load, negative values a benefit. Red dots represent the net impact potential using average energy mix. Net impact potential using a marginal of 100% gas and 100% coal are shown with horizontal narrow boxes. GWP reference: AR4[71]. The number in bracket under each MS label represents the quantity of MSW generated by inhabitant (b) and the total quantity of MSW produced by the MS in million tonnes (c).

From a policy stand point, Figure 3-2 clearly demonstrates that the GWF performance of waste management in Europe is very heterogeneous, despite a common regulatory framework. Some MS (DK, DE), which have strongly promoted the recovery of materials and the recovery of energy from incineration, rank best regarding GWF. This is due, in part, to a stricter regulatory regime than the ‘minimum’ European regime. The performance of DK and DE is so significant that, on a tonne basis, these MS create a significant quantified benefit to society through substitution. This does not mean that we should, as a society, create as much waste as possible to generate indirect GHG sinks (societal benefits), as this will be demonstrated later in the waste prevention section 4 of this thesis.

Nevertheless, these findings provide a strong evidence-based driver that should help less performing MS to rapidly modify their existing waste management system in order to harness the benefits of recycling and energy from waste. This is particularly true in the context of current GHG mitigation. GHG mitigation from waste management is probably one of the easiest technological solutions or “low hanging fruits” in the climate mitigation portfolio due to proven technologies that are readily available and have relatively cheap infrastructure cost compared to other GHG mitigations approaches.

Figure 3-2 also shows that no matter how efficient landfilling is, countries relying principally on those technologies perform less well than countries that have adopted diverse waste management system focusing on the optimisation of resources recovery.

Finally, a very interesting learning outcome from this research exercise is that the ranking of member states according to their national waste management technology proportion, illustrated in Figure 3-3 (% landfilling, % incineration, % recycling and composting) is different than the ranking based on the waste management GWF performance, as illustrated in Table 3-5.

Table 3-5 should be used with great caution because of its inherent simplistic approach and because only one environmental parameter (GWF) is included. However, this table demonstrates that the performance assessment of member states cannot be solely undertaken by structural indicators (relative importance of treatment technologies) alone but should be supplemented with environmental assessment indicators to strengthen evidence for policy development.

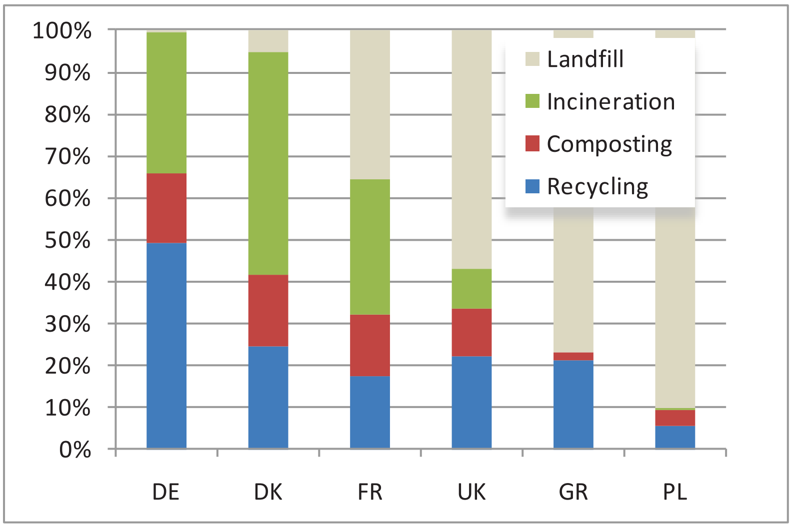

Figure 3-3. Waste management profile of selected member states in 2007 (after Eurostat 2010 with data for 2007)

Table 3-5. Waste management ranking based on Eurostat and GWF

	Eurostat	GWF performance		
Member state (MS)	Landfilling rank	Kg CO_2-eq.t^{-1}	Kg CO_2-eq.kg^{-1}.inh^{-1}	Total t CO_2-eq
Germany	1	1	2	1
Denmark	2	2	1	3
France	3	5	5	6
UK	4	3	3	2
Greece	5	6	6	5
Poland	6	4	4	4

The smallest value represents the least landfilling (first column) and the highest GWF performance (last three columns). The second, third and fourth columns represent the emissions per tonne of municipal waste managed, emissions per kg of municipal waste and per inhabitant and total emission for the member state, respectively. Ranking based on Eurostat data from 2007 and the GWF modelling performed in Gentil *et al.* (III). The ranking was determined using the average energy mix results.

Chapter 3 provided an overview of waste management and anthropogenic climate change with an analysis of the GWF performance of waste management for selected European member states. The analysis showed that member states have very different GWF performance. High GWF performing member states are also the ones who are producing the largest quantity of waste per capita. Some might conclude that “producing more waste is good for the environment”. In truth, one should consider that when waste has been produced, treating it appropriately can generate environmental benefits to society (by substituting primary resources), while disposing of it inappropriately generates environmental loads that impacts negatively on society. If the waste is not produced in the first place, through waste prevention, one might wonder what would be the environmental gain and whether that gain would outweigh or not the benefits of active waste management. An attempt to address these questions is presented in Chapter 4.

4 Municipal waste prevention

Waste production seems always positively correlated to economic growth. Some organisations, such as the OECD, have challenged this and have engaged actively in waste prevention discussions, where focus was mainly on the definition of terms and the development of prevention indictors, as early as 1999[75].

Waste prevention, in Europe, is now part of the European regulatory system and is considered to be the most preferable waste management option (directive 2008/98/EC[34]). The ultimate waste prevention indicator, and the most agreed upon, is the annual quantity of waste produced compared to the previous year, within a given region. If the quantity of waste has decreased, independent from GDP and population fluctuations, it is safe to claim that (absolute) waste prevention is achieved. In Europe, only relative prevention, or decoupling, has taken place (waste growth has increased less rapidly than GDP growth, but waste production has continued to increase). While waste production statistics have a fundamental value for policy making, it is not a 'complete' indicator, because there is no environmental assessment information, so it is not possible to know the environmental consequences from the reduction of waste. Here, it is proposed to quantify the environmental consequences of waste prevention.

Numerous studies have been carried out on refining waste prevention indicators, on determining the mechanisms that lead to the prevention of waste and case studies explaining successful waste prevention activities[76, 77, 78, 79].
The focus of Gentil *et al.* (IV) paper is not to investigate how prevention can be achieved but what would be the environmental consequence when waste has been prevented. If environmental quantification of waste prevention can be determined, it is believed that it could reinforce the importance of waste prevention at policy level.

4.1 Methodology

The immediate challenge for modelling waste prevention is to develop a conceptual model that can be incorporated in existing waste LCA models, such as EASEWASTE, without violating the fundamental rules of LCA methodology (system boundary and functional unit consistency are the most important). The overall concept for the environmental quantification of waste prevention is to compare two waste management systems that only differ by the amount and type of waste prevented (Figure 4-1). In order to respect the functional unit (*i.e.* the same amount of waste entering the waste management system whether there is prevention or not), a 'virtual' waste flow was created, representing the quantity and type of the waste prevented. This flow has no burden. When two waste management systems are compared, it is possible exclude the upstream impacts associated with the production of goods leading to the waste (zero burden approach) to simplify the modelling.

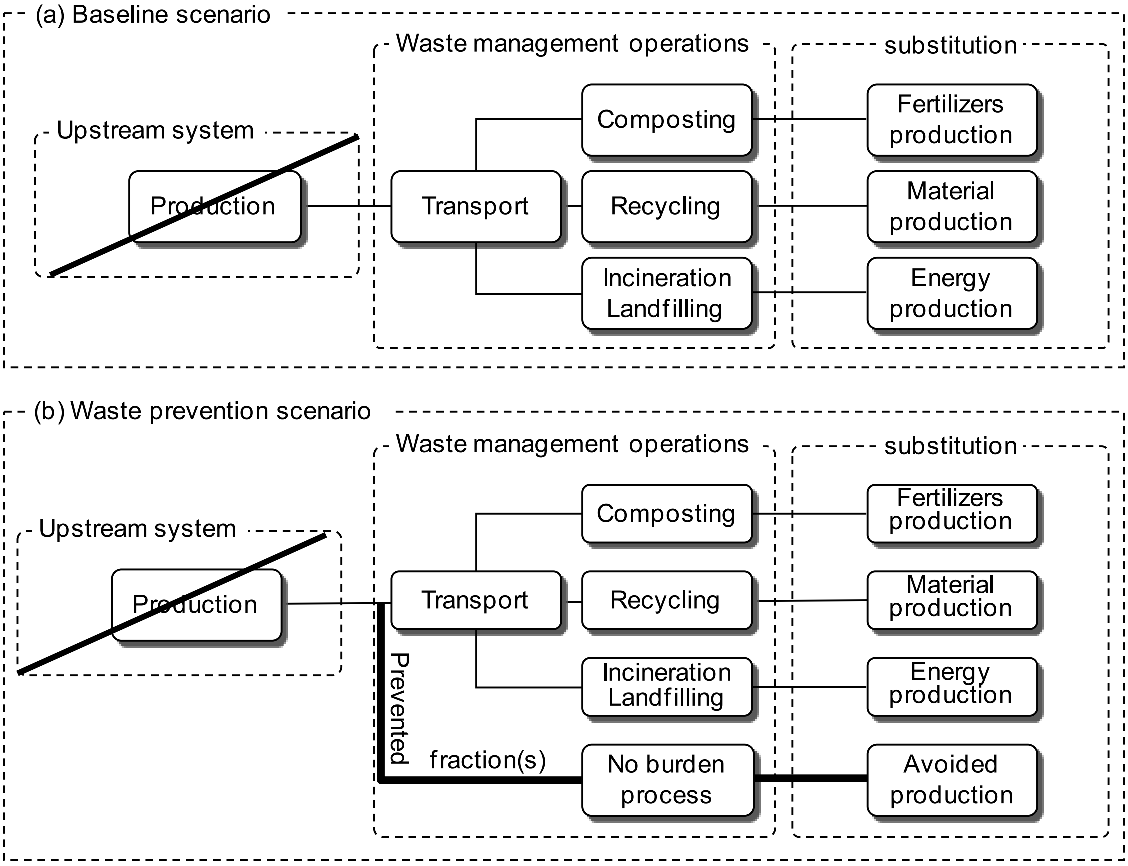

Figure 4-1. Conceptual diagram of waste prevention modelling (Gentil *et al.*, IV)

However, when prevention takes place, some upstream production processes are likely to be affected, proportionally to the amount of waste prevented. Hence, the use of 'partial' zero burden approach. This approach has been modelled in Gentil *et al.* (IV) and has also been documented by Cleary[80]. For instance, if 10 % plastic bottles is prevented (through a reuse scheme), it can be inferred that about 10 % of the load and benefits from the waste system will be avoided and about 10 % of these bottles will not be produced, leading to avoided impacts from the avoided production.

In this study, waste prevention is assessed for beverage packaging (plastic and glass), food waste (meat and vegetables), and unsolicited mail. One of the objectives of the study was to use realistic waste prevention potential for these fractions. Table 4-1 provides a summary of the fractions with their assumed proportion in the waste system and their prevention levels.

Table 4-1. Proportion and prevention levels in selected waste fractions

	Proportion in the waste	Prevention levels
Vegetable waste	25%	20%
Meat waste	7%	20%
Glass beverage packaging	6%	60%
Unsolicited mail	6%	20%
Plastic beverage packaging	1%	60%

These fractions were used to highlight different approaches to waste prevention:

- glass beverage packaging: prevention through packaging reuse;
- plastic beverage packaging: prevention through packaging reuse;
- vegetable waste: highest proportion in MSW composition;
- meat waste: high environmental production costs; and
- unsolicited mail: easiest prevention to achieve.

In order to get a broader understanding of the environmental consequences of prevention, two types of waste management systems were modelled; a low technology system and a high technology system. The first waste management system, "Low-tech.", depends mainly on engineered landfilling for the disposal of the residual waste, but it also includes biotreatment and a lower level of recycling compared to the second system, "High-tech.", which principally treats residual waste through thermal treatment with energy recovery. The high-tech system also includes a higher level of recycling. For both systems, the same assumptions were used for the level and types of waste prevented.

4.2 Outcomes of the study

For didactic reasons, it is important to present the results in a stepped approach: 1) Influence of prevention on waste management systems, excluding avoided production, 2) Influence of prevention on overall supply chain, including avoided production, 3) Influence of prevention in different waste management systems, 4) Influence of prevention on waste management technologies and finally 5) Cascading consequences of waste prevention.

Influence of prevention on waste management systems, excluding avoided production. This part of the study indicates that when combined prevention is implemented (all waste fractions subject to prevention in the study), the loads and benefits of the affected waste management system are reduced. No big surprise here. However, it was interesting to see that the different impacts where affected differently. This is mainly due to the change in waste quantity and the change in elemental waste composition after prevention. An increase in human toxicity via water was observed because of the added transport and washing cycle of the returnable packaging (prevention through reuse). However, this was considered insignificant.

Influence of prevention on overall supply chain, including avoided production. When waste is prevented, it is fair to assume that an equal amount of production emissions is avoided as a consequence of waste prevention. This is called avoided production. When avoided production is factored in the modelling, significant environmental savings are observed. Most of the savings are linked to the prevented meat and vegetable waste. More precisely, the prevention of meat waste is avoiding the production of meat, which in turns avoid fertilizer use, hence the reason for the saving in nutrient enrichment when meat waste is prevented.

Influence of prevention in different waste management systems. A comparison of a high technology waste management system and a low technology system is performed with the same waste prevention parameters. In absolute terms, the high-tech system performs better than the low-tech system with and without prevention. This is because of the substantial environmental savings from material recycling and energy from waste. Relatively speaking, the biggest progress due to waste prevention comes from the low environmental performance waste management system. This clearly indicates that municipalities that do not have good waste infrastructure in place can achieve significant improvement in their environmental performance, when undertaking prevention schemes.

Influence of prevention on waste management technologies. The modelling of waste prevention on individual technologies indicates that a relatively small prevention level (13 % of the total waste mass is prevented in the study) has an almost insignificant effect, however a significant benefit is generated from the avoided production.

Cascading consequences of waste prevention. When paper is prevented (here unsolicited mail), wood pulp that would otherwise be used by the paper industry is available. In an actively managed forestry system, it can be expected that the excess wood could be used for energy production, potentially substituting fossil energy. The study indicates that when the cascading effect is factored in the assessment, the benefits of unsolicited mail prevention are increased significantly for most environmental categories, despite a larger uncertainty due to the cascading effect.

This research work has highlighted and quantified some of the environmental consequences of waste prevention, such as the consequences on the waste management systems (loads and benefits), specific waste management technologies, supply chain (upstream avoided production) and cascading effects. However, it is clear from this study that much more detailed consequential assessment should be performed. For instance, it is believed that the rebound effect of waste prevention (preventing waste could lead to the production of another waste or another activity) could have a significant influence on the LCA results and should be modelled in future studies.

5 Conclusions

5.1 Concluding remarks

Waste management in Europe has undergone profound changes since the early 70s. Waste has increased substantially and become more diversified, with the growing number of regulations put in place to mitigate impacts on human health and the environment. This strong regulatory system and the implementation of financial instruments (landfill tax) have led to a large increase in waste treatment facilities and technology types across Europe. Most of these complex waste management systems necessitate computer models, such as waste LCA models to assess and potentially optimise the environmental performance of these systems.

Waste LCA model review (Gentil *et al.*, I). The in-depth review of the different waste LCA models showed that the models include different levels of detail depending on when they were developed (Gentil *et al.*, I). The review also indicated that waste LCA models should not be numerically compared without a careful assessment of technical assumptions defining each waste management technology and their underlying external inventory databases. Waste LCA models have evolved at different time and technology data tend to be country specific, which makes inter-model comparison difficult. A robust comparison of waste models requires a very good understanding of the parameters across the different models in order to select only the common parameters. The review work has also enabled to highlight issues that should be included in future development of waste LCA models.

Waste management and climate change (Gentil *et al.*, II, III). Waste LCA models are used to determine the environmental performance of waste management systems. Global warming potential is one of the environmental impacts routinely analysed in LCA models. The importance and significance of anthropogenic global warming, despite not new, is a widely accepted concern in today's society. The investigation of waste management issues and climate change (Gentil *et al.*, II) has identified that greenhouse gases accounting methodologies use similar data (GHG from waste management activities) but have different objectives and therefore their interpretation can be confusing for waste management stakeholders not familiar with the methodological intricacies of the protocols. Four groups of accounting methodologies have been identified (trading schemes, life cycle assessment, organisational accounting and national accounting). It is suggested that these mechanisms can all be integrated in one reporting framework that encompass the operating waste management activities, with the upstream activities (energy, ancillary material input, ...) and the downstream activities (recovery of material and energy), called the UOD framework. The great advantage of the UOD framework lies in its simplicity and transparency for reporting and communicating to a wide range of stakeholders. Depending on the reporting / accounting scope, the user can select only a part of the framework.

Based on the acquired knowledge on climate change and waste management, a global warming factor performance assessment was carried out for six European member states, using life cycle thinking (Gentil *et al.*, III). The most significant outcome of that study is that all the member states, except Greece, are generating environmental benefits (at societal level) because a significant quantity of waste managed by those member states is "valorised" through materials and energy substitution. The study also highlighted wide performance differences between member states, despite common regulatory system. This should give a clear illustration to policy makers that it is possible to increase the waste management performance of member states by facilitating appropriate knowledge and technology transfers that could contribute towards further GHG mitigation.

Municipal waste prevention (Gentil *et al.*, IV). Waste prevention is imbedded in the latest European waste framework directive (2008/98/EC) but little is known about the environmental consequences of waste prevention. The environmental assessment of waste prevention indicated that a relatively minor waste prevention could lead to significant environmental savings due to avoided upstream production and cascading effects (Gentil *et al.*, IV). The benefits of waste prevention are obviously different between different waste fractions since the prevention benefits are related to the proportion of the fractions in the waste, its realistic potential for prevention, the avoided load and benefits of waste treatment and its avoided production. The benefits of waste prevention also depend on the type of waste management system, but to a lesser extent, as most of the benefits of prevention take place upstream from the waste management system. The prevention of meat waste was found to have the greatest benefit, compared to the other fractions studied. The environmental quantification of prevention should be used as a strong indicator to further strengthen the importance of this waste management approach.

5.2 Recommendations and further research

A number of recommendations can be drawn for this PhD study;

Improve substitutional data of materials and energy. It is clear from the substantial evidence found in the literature, from numerous LCA studies, that waste management, if carried out appropriately, generates significant environmental benefits to society, by substituting raw materials and fossil-based energy. It is also clear that the range of results is relatively large. The critical issue is to improve the robustness of the substitutional data of materials and energy. Obviously, this is a major task which is relatively new to the waste management research community, as researchers have been primarily focused on improving waste management models through the often tedious compositional analyses of waste, energy system analyses, material flows analyses and the assessment of waste management technologies to evaluate waste specific and technology specific environmental emissions.

The emission factors (for GWP as well as other impact categories) of recycling and energy from waste are dependent on a number of factors; commodity price of recyclables and virgin materials (market elasticities), due to supply and demand of those materials which means that emission factors can change regionally and from year to year. Emissions factors of recyclables are also affected by the energy mix assumed for the recycling process. For instance sending recyclables to a country with a carbon intensive mix, will be worse than undertaking the same recycling in a country with a low carbon intensity energy mix.

Probabilistic assessment of marginal materials and energy. An increasing number of authors are recommending the use of consequential LCA. The main barriers for the implementation of consequential LCA is that obtaining robust data is extremely time consuming, especially when marginal data varies regionally and from year to year. It could be very valuable to investigate the probability of marginal energy or material using a probabilistic approach. For instance, we should be 100 % certain of the average marginal electricity mix for 2009 in Denmark. We should have a high level of certainty for the current year. The certainly level of the marginal decreases each year in the future. When attempting consequential LCA for longer time, let's say 20 years in the future, the probability that a particular marginal will be used is quite low, as the future is inherently uncertain. It is probably more rigorous at this stage to undertake a number of scenarios with different marginals. There is no reason why this approach could not be adopted for the determination of marginals for materials (to obtain more robust recycling LCAs).

A probabilistic assessment of marginal data would be very useful for waste LCA practitioners and waste management researchers because it would enable the users to focus on waste management system modelling while having a known level of confidence on the marginal data.

5.3 Looking at the broader perspective

This research work has confirmed that European waste policy was on the right environmental track, although much more improvement can be achieved. Waste stakeholders are rapidly realising that managing waste appropriately can lead to successful resource management that can generate financial returns and environmental savings, and if jobs are created, we could be very close to sustainable waste management practice. The question is whether the European example of integrated waste management could be replicated outside Europe in growing economies. The answer is complex as there is not a single ideal system and replicating European waste management system blindly could lead to unforeseen environmental, social and economical impacts as pointed out by Wilson *et al.*, 2010[81]. It is clear, nevertheless, that some knowledge, technology and capacity building should be transferred outside Europe, while insuring that the informal sector is factored in.

A second question, more specific to GHG mitigation, is why the technical solutions developed by the waste industry and demonstrated through extensive applied research has not been recognised as one of the many contributors towards GHG mitigation? Two answers to that: 1) waste is broadly perceived as a negative and unwanted activity, detrimental to the environment and human health, and to most areas in the world, it is still the case. 2) Communication of research findings and industry development have not yet permeated to the political and general public spheres. The waste industry has developed a number tools and GHG mitigation solutions, often promoted by strict regulation enforcement, which now require to be replicated and rolled out globally, to ensure that waste with impacts becomes resources with savings.

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Appendices

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